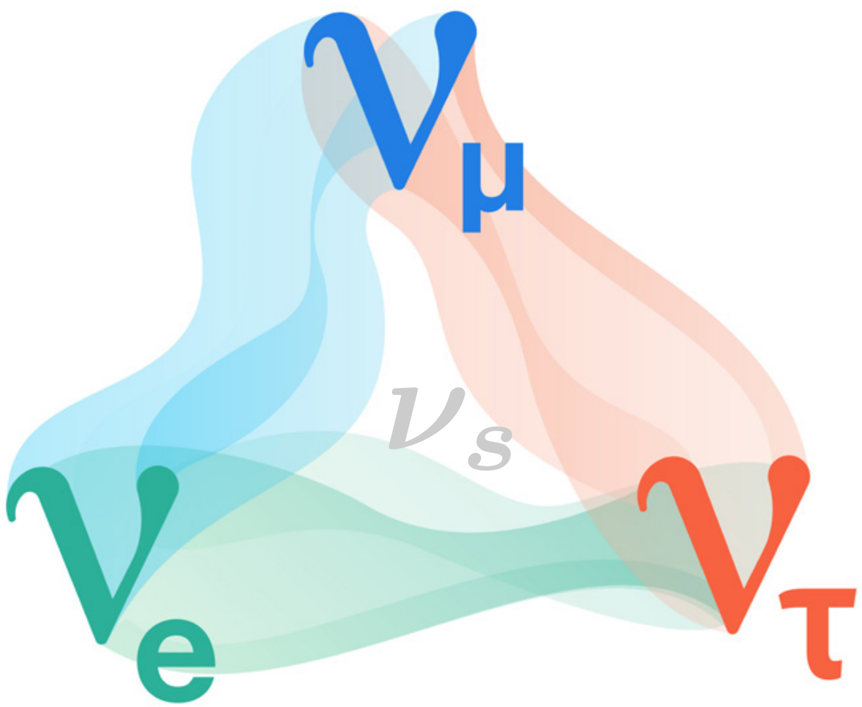
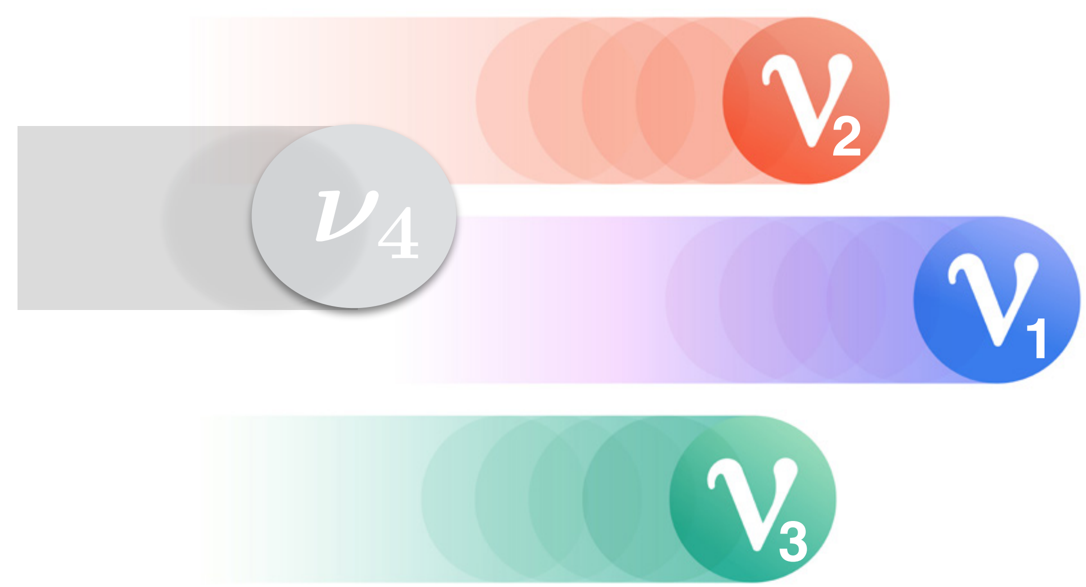
" Δm^2_{21} Measurements and Tensions "

Stephen Parke
Fermilab

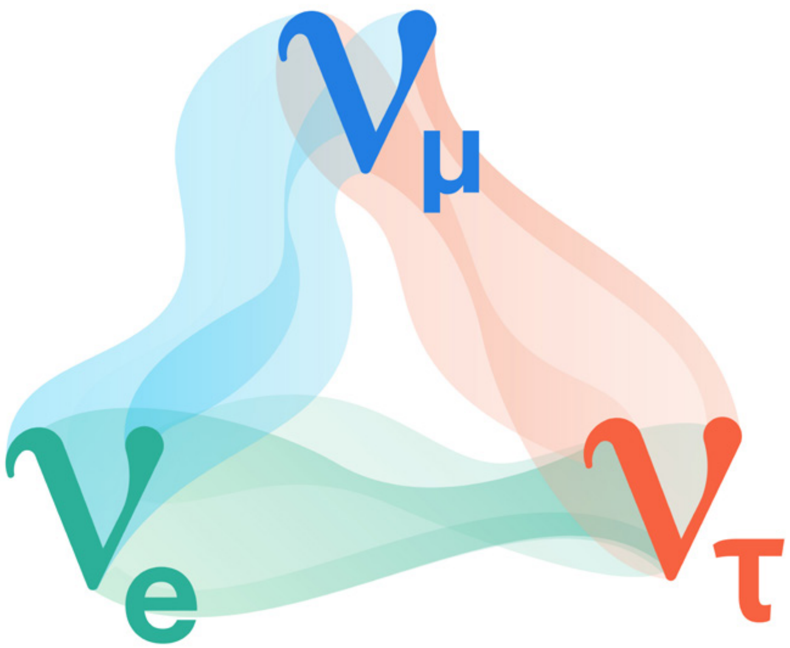




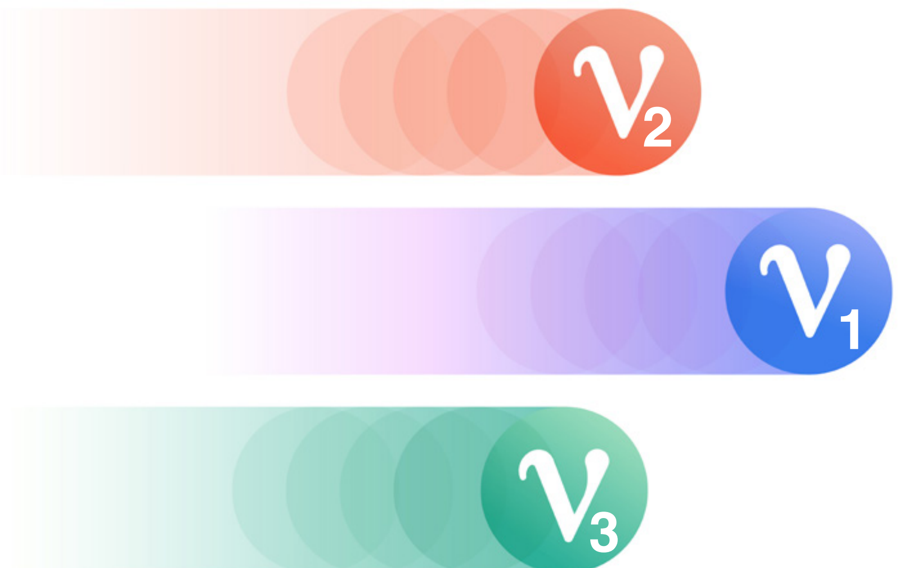
Interactions:

simple

complicated



$= U$



unitary matrix ?

complicated

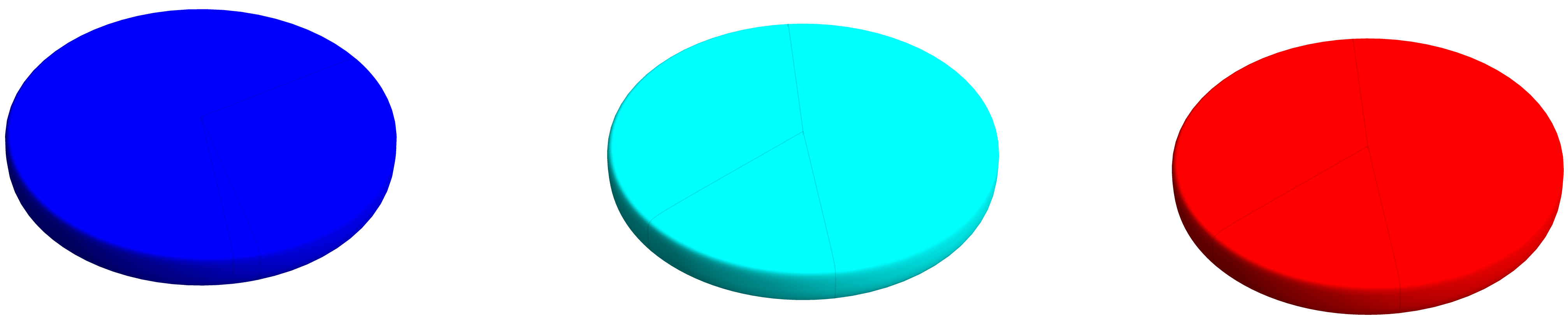
simple

masses ?

Propagation:

Neutrino Flavor or Interaction States:

$W^+ \to e^+\nu_e$ $\quad$ $W^+ \to \mu^+\nu_\mu$ $\quad$ $W^+ \to \tau^+\nu_\tau$



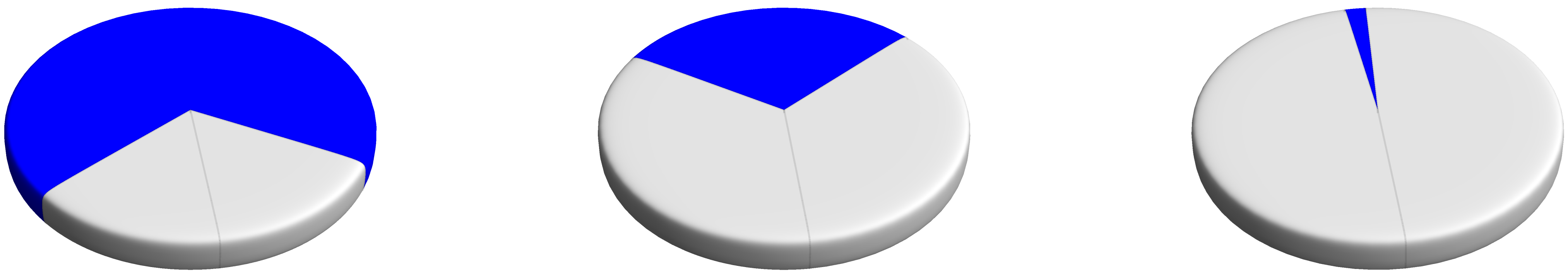
ν_e $\quad$ ν_μ $\quad$ ν_τ

provided $L/E \ll \mathbf{0.5}\ \mathrm{km/MeV} = \mathbf{500}\ \mathrm{km/GeV}$!!!

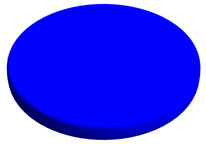
$\sim$ 1 picosecond in Neutrino rest frame !!!

Neutrino Mass EigenStates or Propagation States:

Propagator $\nu_j \to \nu_k \;= \boldsymbol{\delta_{jk}\, e^{-i\left(\frac{m_j^2 L}{2E_\nu}\right)}}$



$\boldsymbol{\nu_1}$ $\boldsymbol{\nu_2}$ $\boldsymbol{\nu_3}$

$\boldsymbol{\nu_e =}$ 

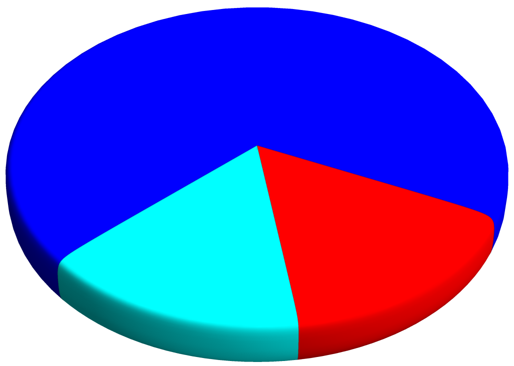
$\boldsymbol{\Delta m^2_{21} \sim 7.5 \times 10^{-5}}$ **eV**^{2}

$\boldsymbol{|\Delta m^2_{31}| \approx |\Delta m^2_{32}| \sim 2.5 \times 10^{-3}}$ **eV**^{2}

Neutrino Mass EigenStates or Propagation States:

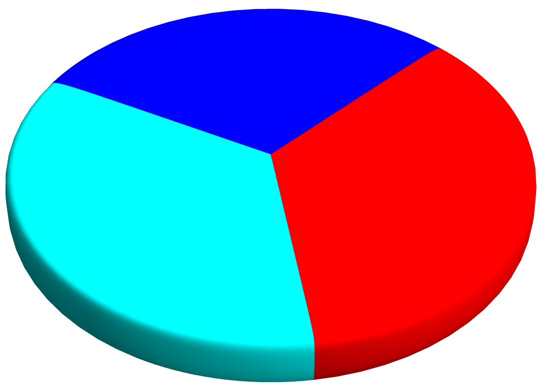
ν_1

most ν_e



δ, θ_{23}

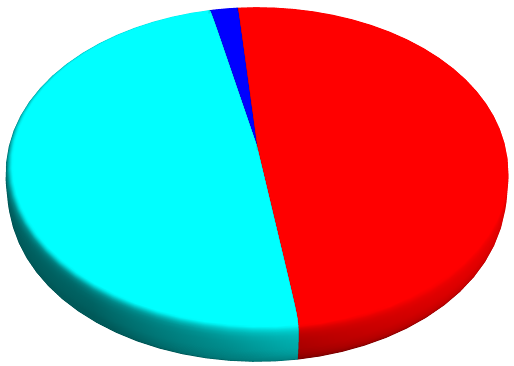
ν_2



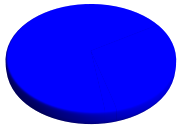
δ, θ_{23}

ν_3

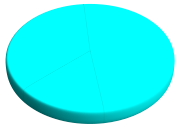
least ν_e



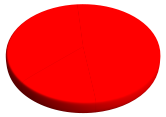
θ_{23}

$\nu_e =$ 

Solar Exp, SNO
KamiLAND
Daya Bay, RENO, …

$\nu_\mu =$ 

SuperK, K2K, T2K
MINOS, NOvA
ICECUBE

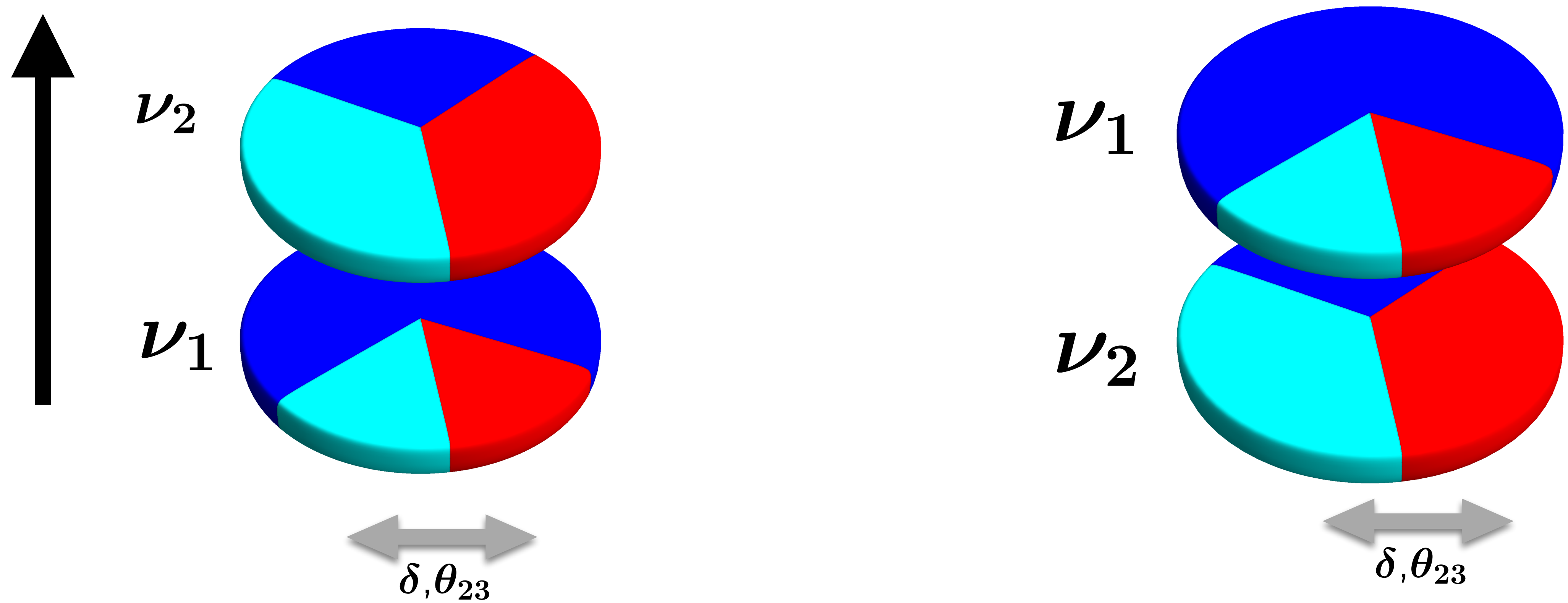
$\nu_\tau =$ 

Unitarity
SK, Opera
ICECUBE ?

$\nu_1, \ \nu_2$ Mass Ordering:

–solar mass ordering

mass



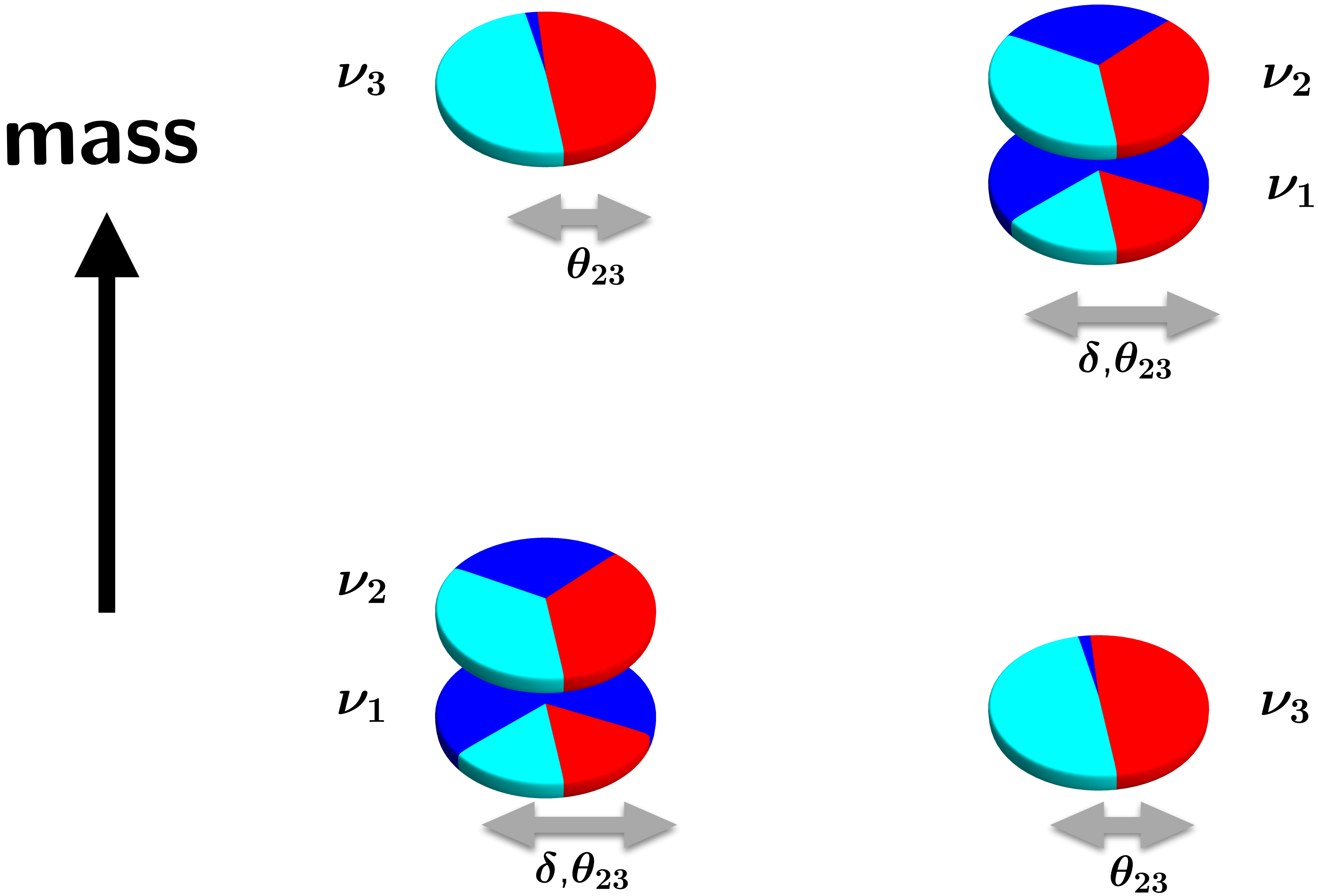
$|\Delta m^2_{21}| = |m^2_2 - m^2_1| = 7.5 \times 10^{-5}\ \mathrm{eV}^2$ $\quad L/E = 15\ \mathrm{km/MeV} = 15,000\ \mathrm{km/GeV}$

SNO $\quad m_2 > m_1$

$\nu_e =$ $\quad \nu_\mu =$ $\quad \nu_\tau =$

ν_3, ν_1/ν_2 Mass Ordering:

–atmospheric mass ordering



$$\sin^2\theta_{12} \sim \frac{1}{3}$$

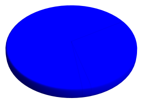
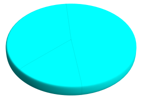
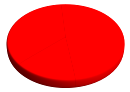
$$\sin^2\theta_{23} \sim \frac{1}{2}$$

$$\sin^2\theta_{13} \sim 0.02$$

$$0 \leq \delta < 2\pi$$

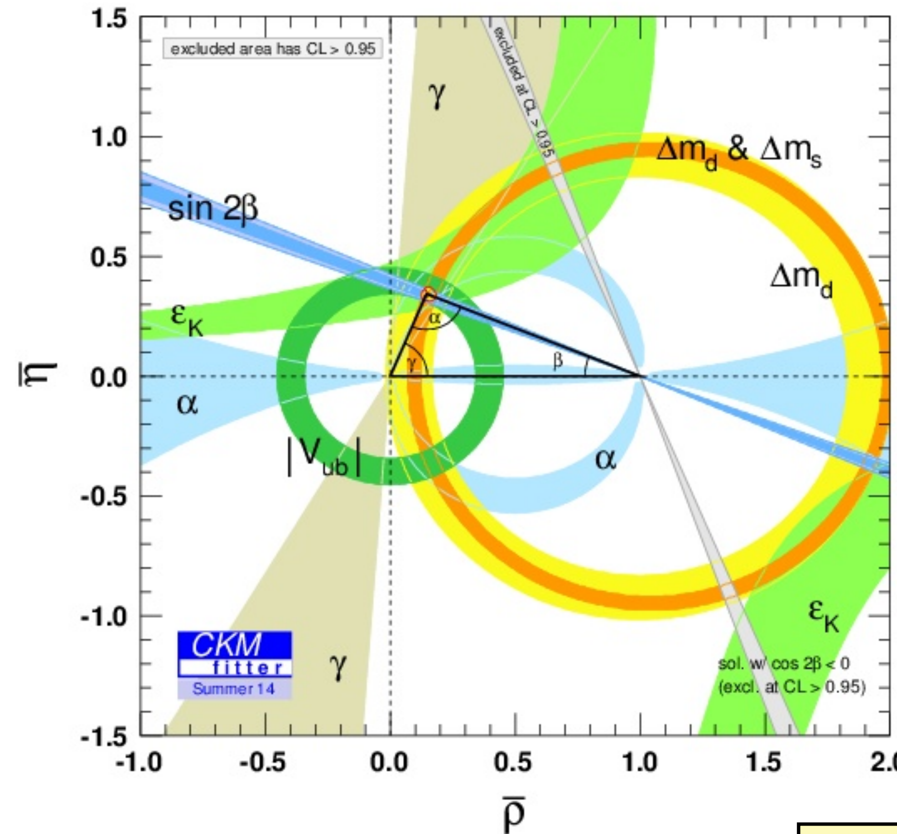
$$|\Delta m^2_{31}| = |m^2_3 - m^2_1| = 2.5 \times 10^{-3}\ \mathrm{eV}^2 \qquad L/E = 0.5\ \mathrm{km/MeV} = 500\ \mathrm{km/GeV}$$

Unknown: NOνA, JUNO, ICECUBE, DUNE, T2HKK....

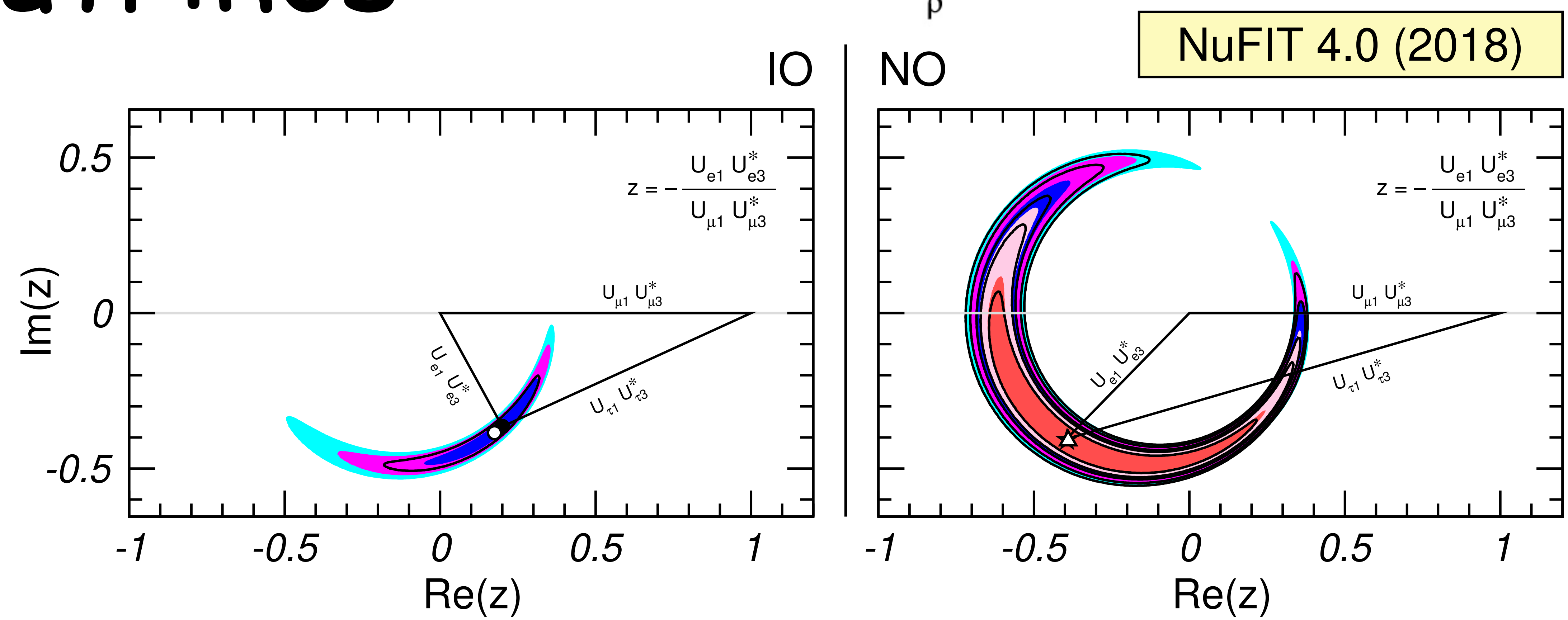
$\nu_e =$  $\nu_\mu =$  $\nu_\tau =$ 

quarks

Unitarity NOT assumed

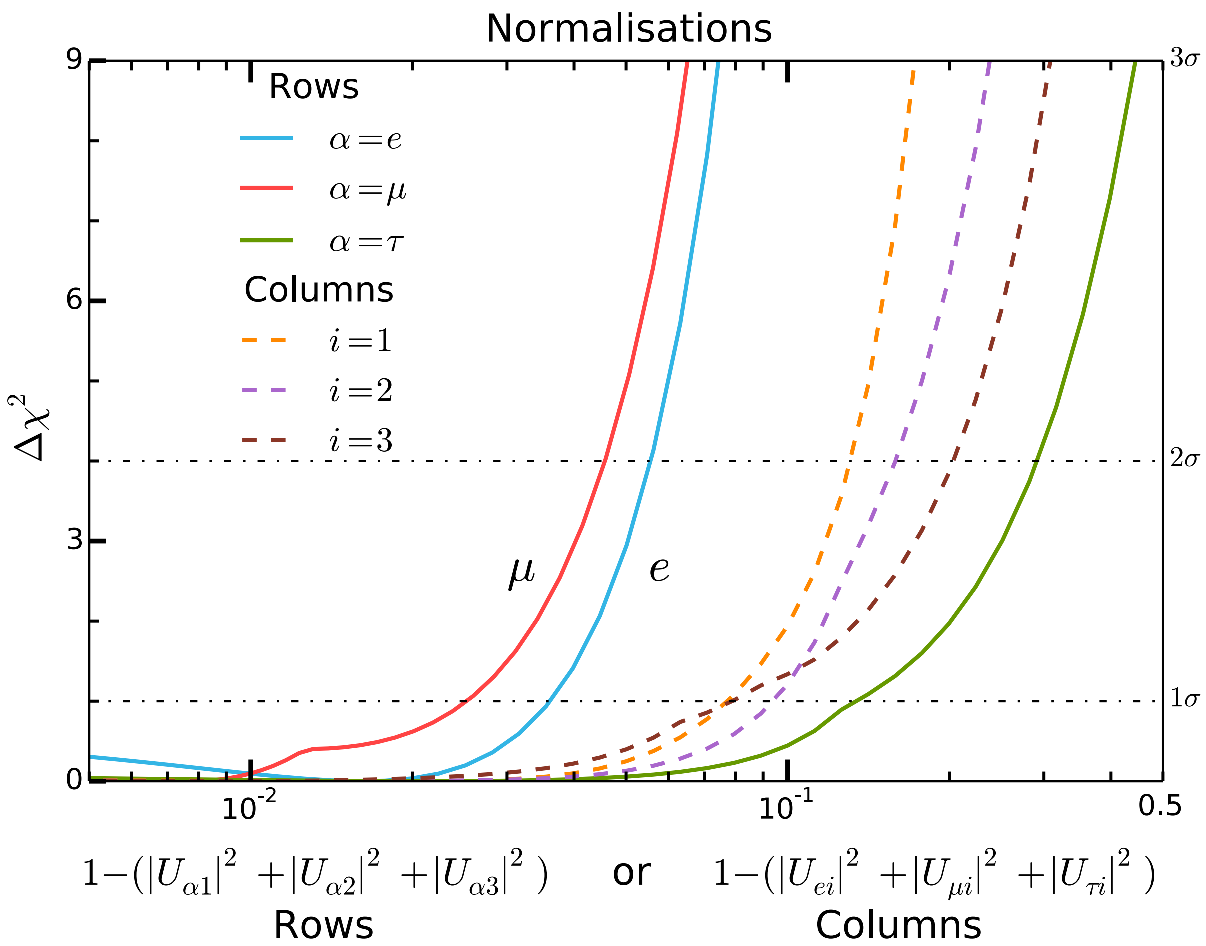


neutrinos



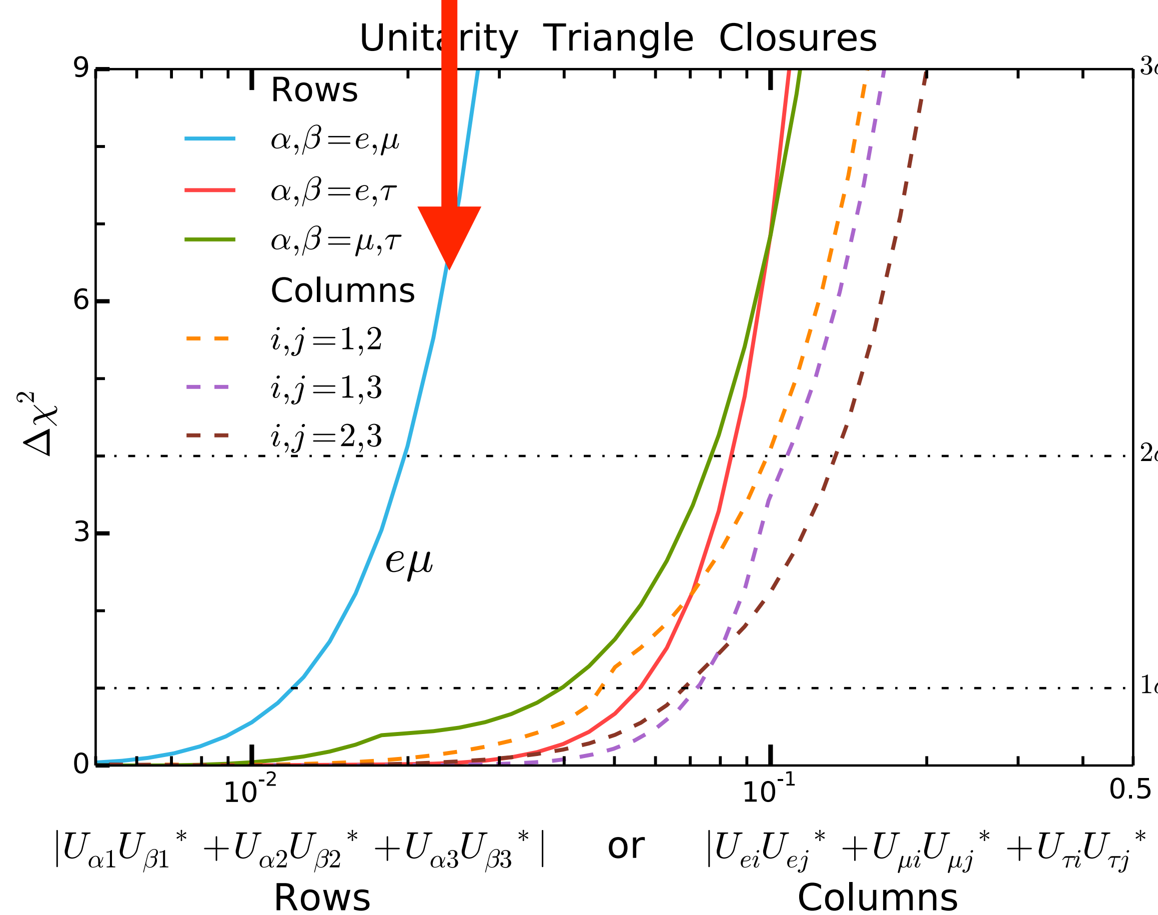
Unitarity Is assumed

Unitarity ???



Ross-Lonergan+ SP 1508.05095

LSND, mB

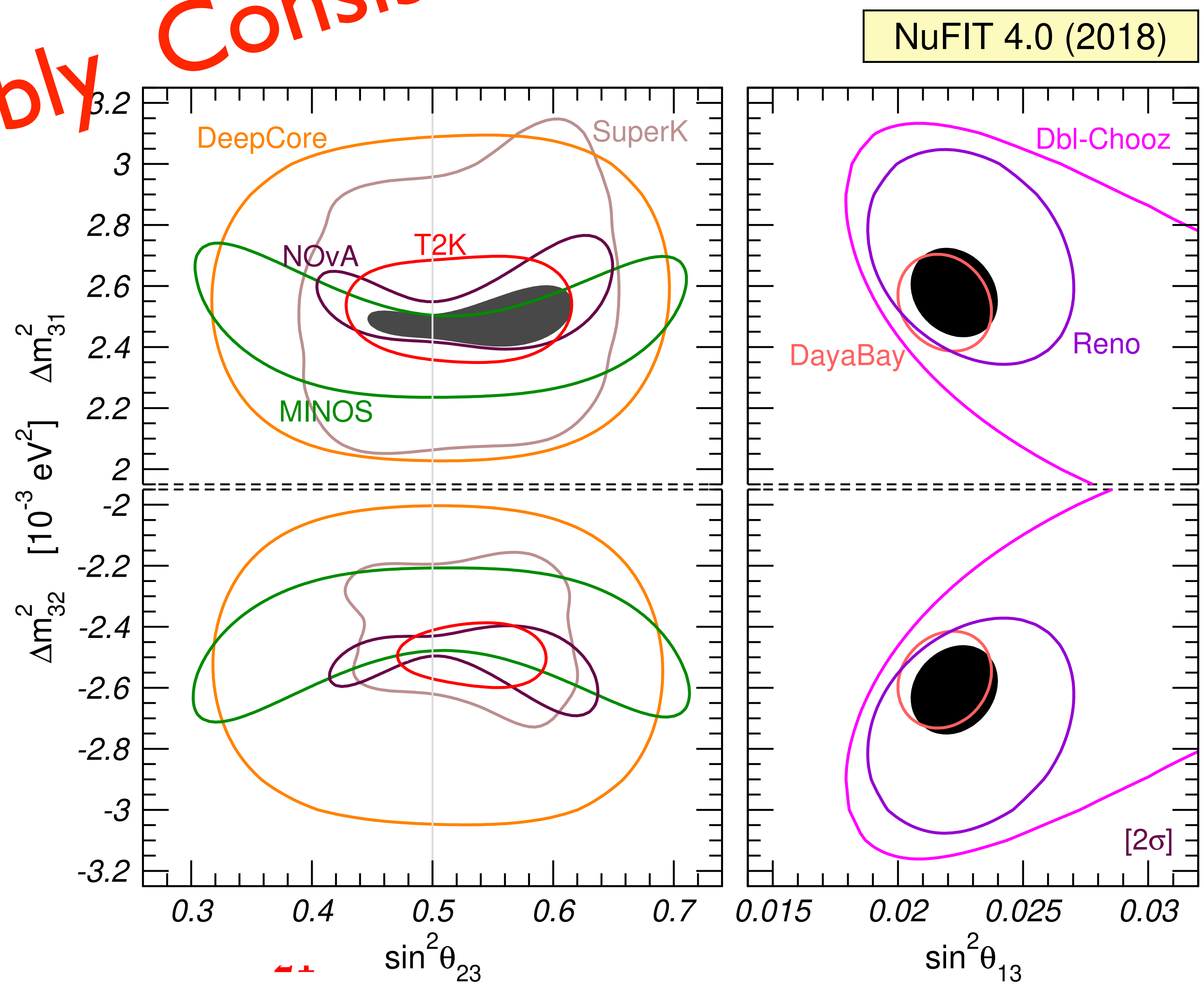


6 row/column plus 6 triangle conditions

2 row and 1 triangle, independent of ν_τ

Δm^2_{atm} v $\sin^2\theta_{23}$ $(\sin^2\theta_{13})$ consistency ?

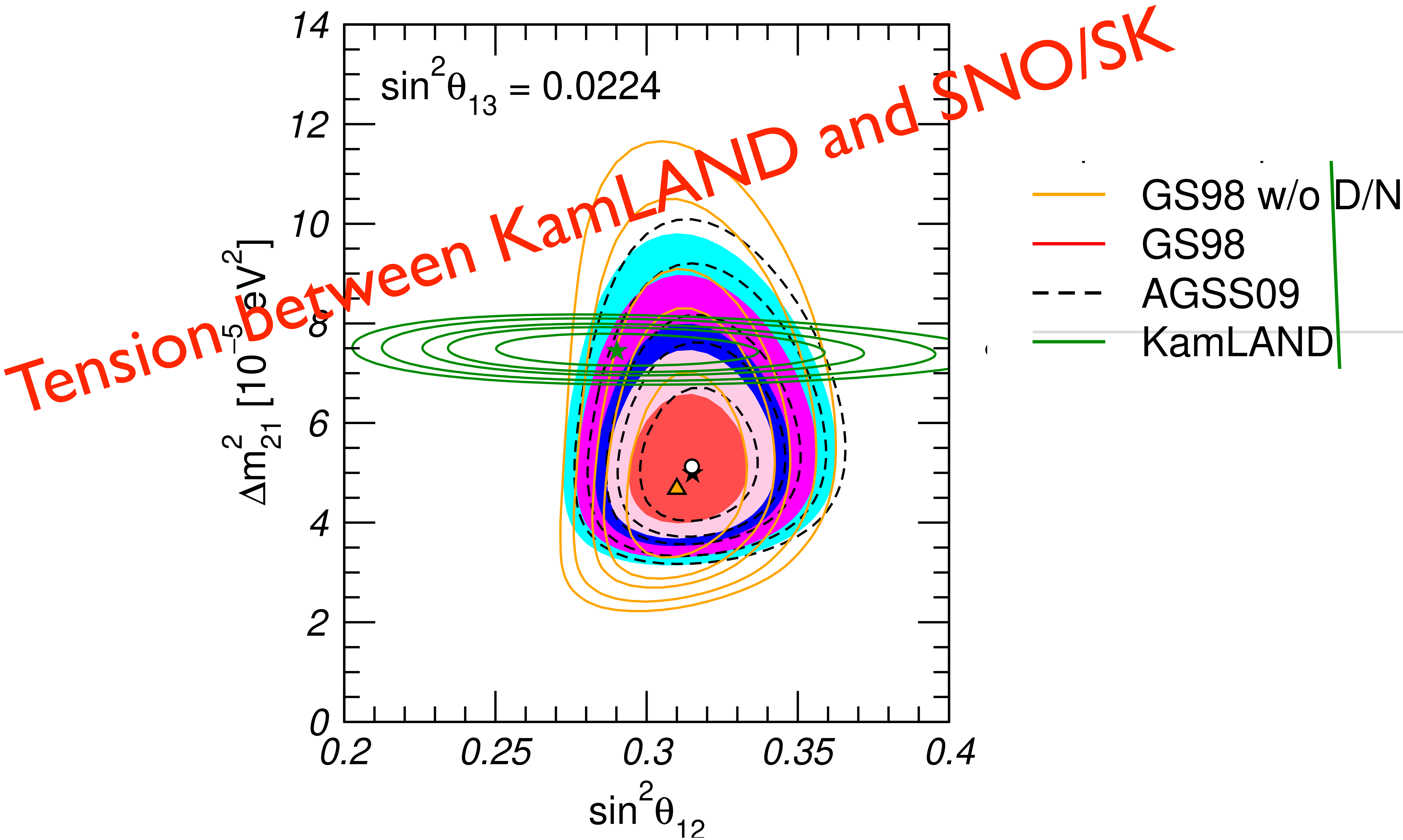
Reasonably Consistent



$$|U_{\mu3}|^2 = c^2_{13}\sin^2\theta_{23}$$

$$4|U_{\mu3}|^2(1-|U_{\mu3}|^2)$$

Δm^2_{21} v $\sin^2\theta_{12}$ consistency ?



1σ, 90%, 2σ, 99%, 3σ CL for 2 dof

Why do we care about Δm^2_{21}

CP Violation:

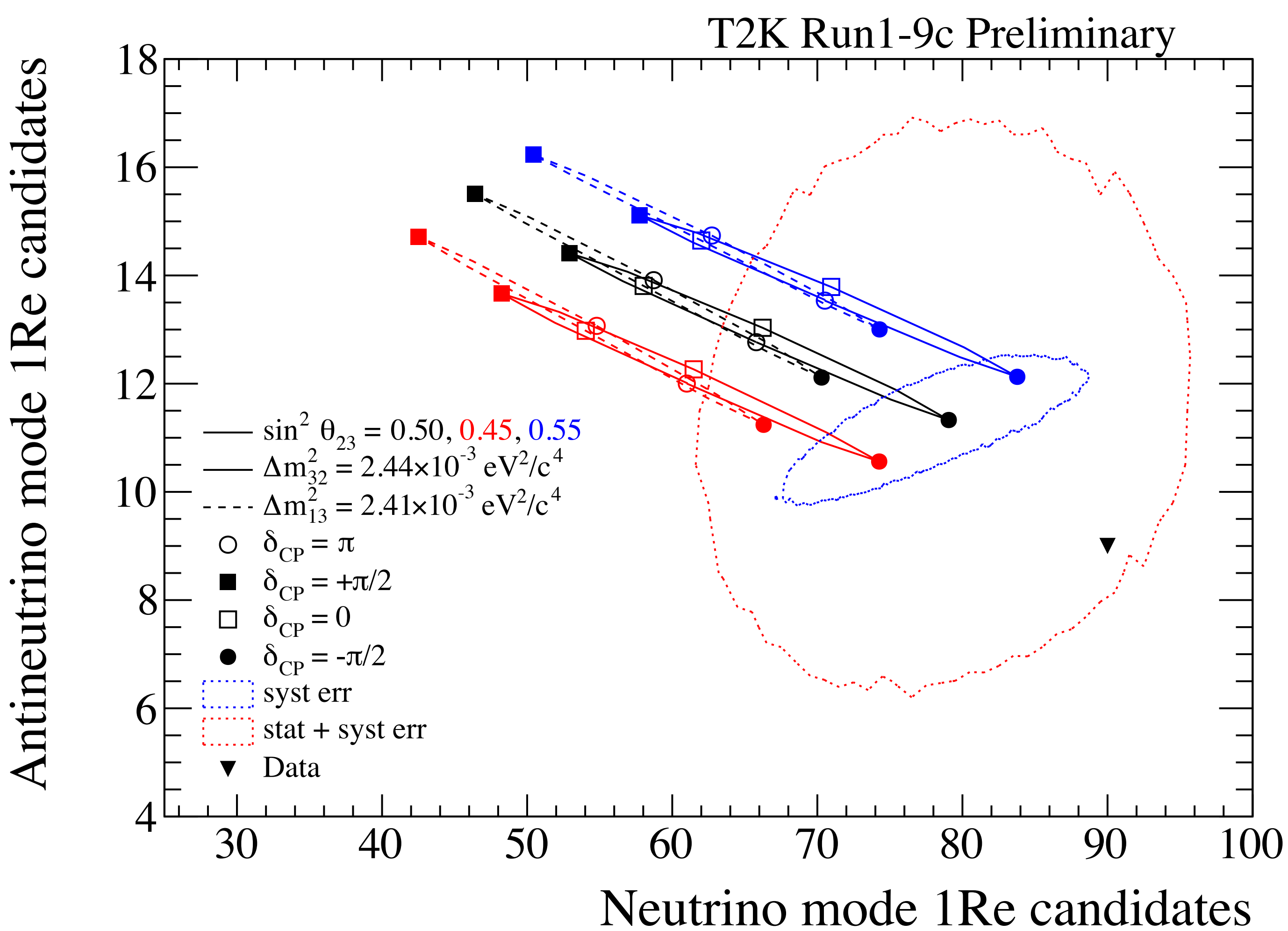
At oscillation maximum in vacuum:

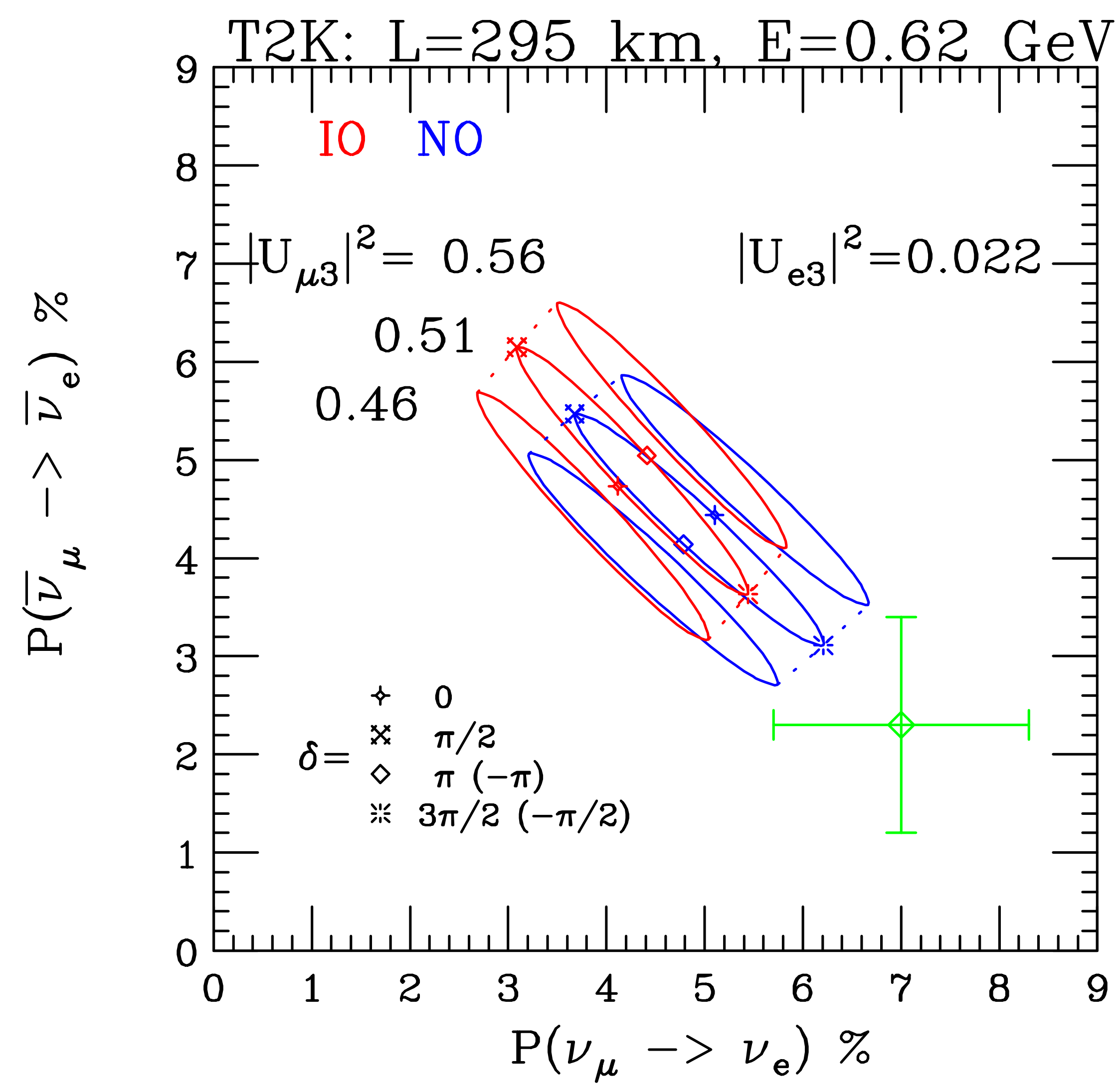
$$P(\bar{\nu}_\mu \to \bar{\nu}_e) - P(\nu_\mu \to \nu_e) \approx \pi J \left(\frac{\Delta m^2_{21}}{\Delta m^2_{31}} \right)$$

where J is Jarlskog Invariant (1985):

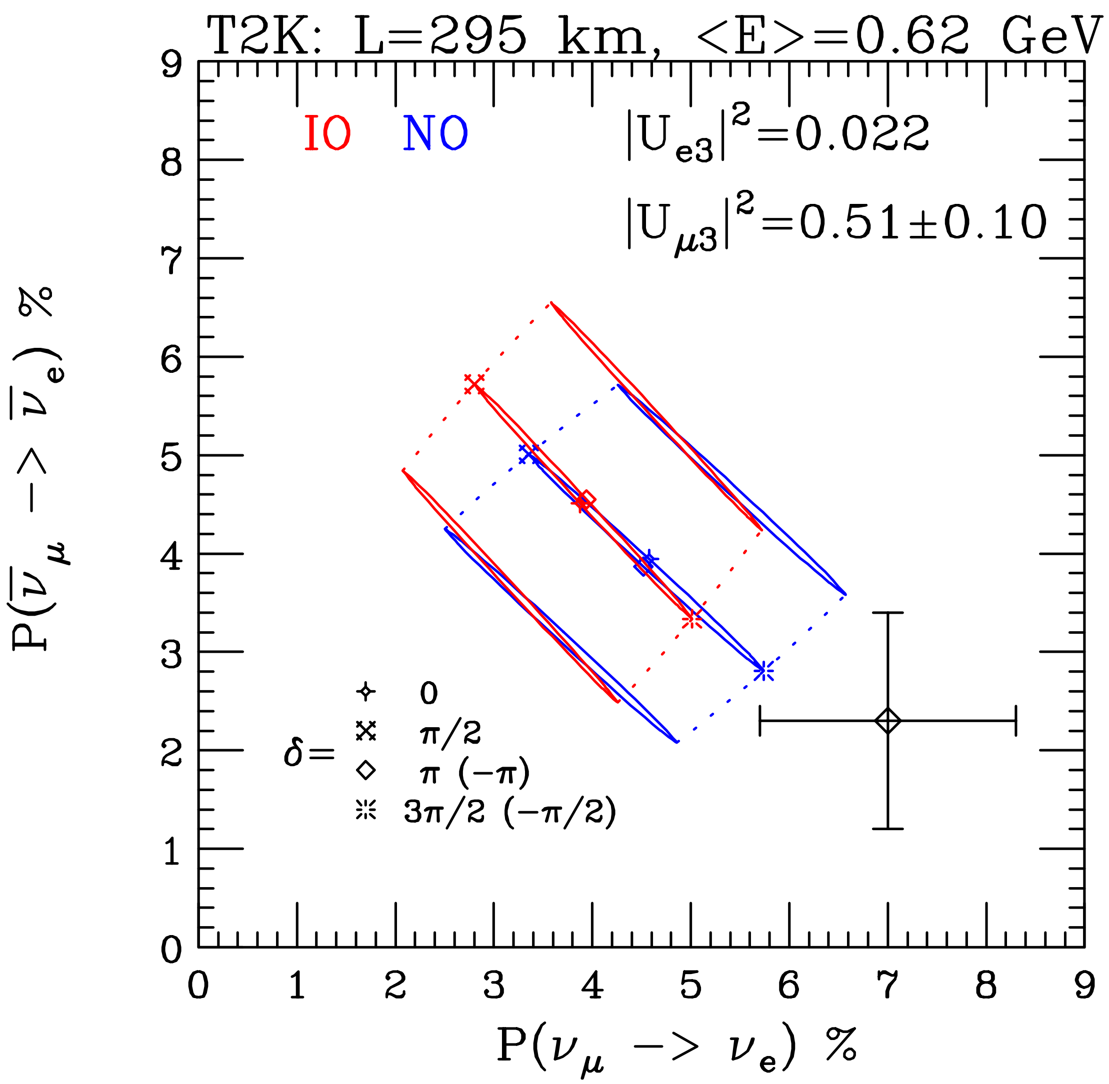
$$J = \sin 2\theta_{12} \sin 2\theta_{13} \cos\theta_{13} \sin 2\theta_{23} \sin\delta \approx 0.3 \sin\delta$$

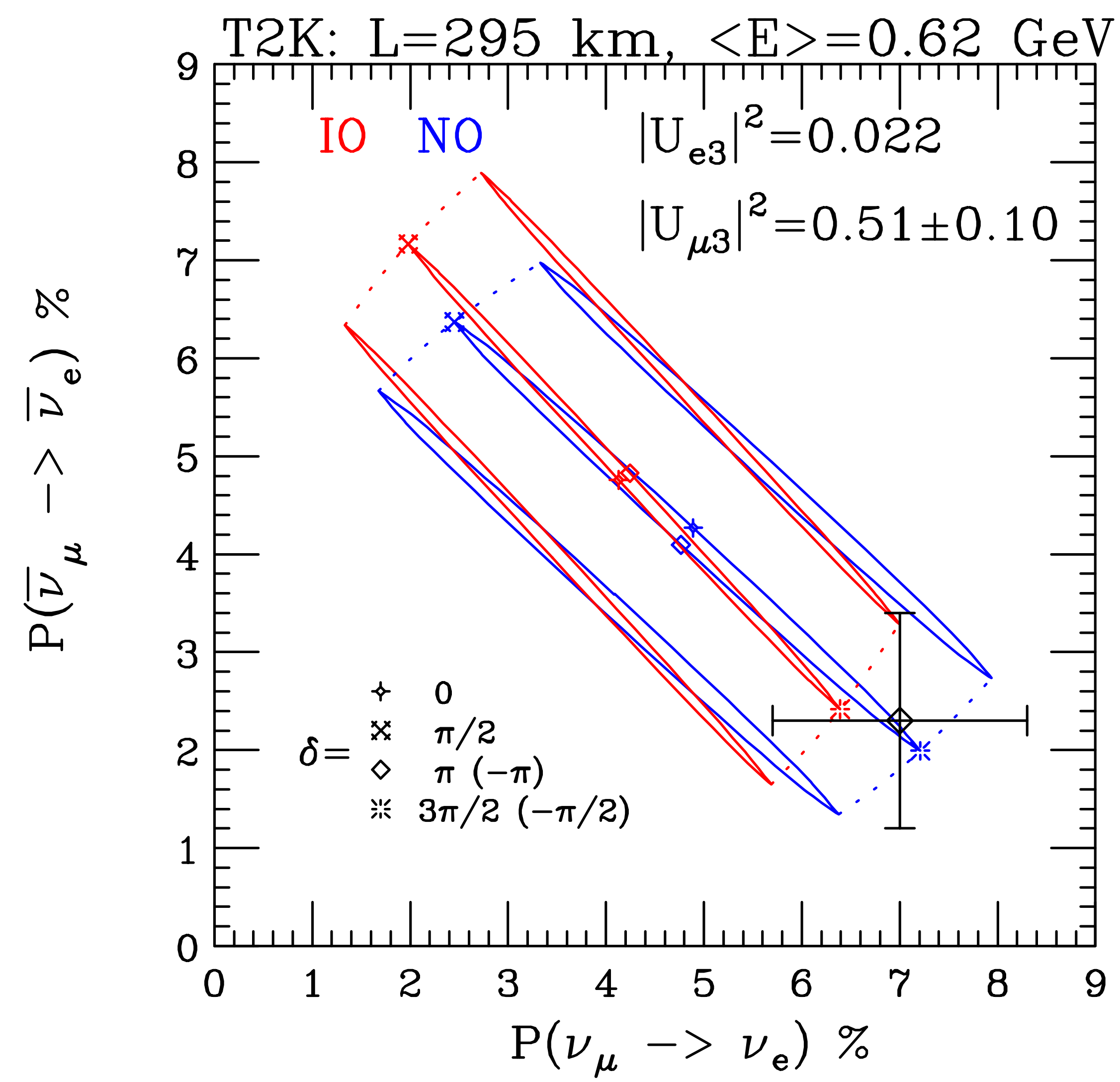
T2K





bi-event: bi-probability:





KamLAND

$$\Delta m^2_{21}$$

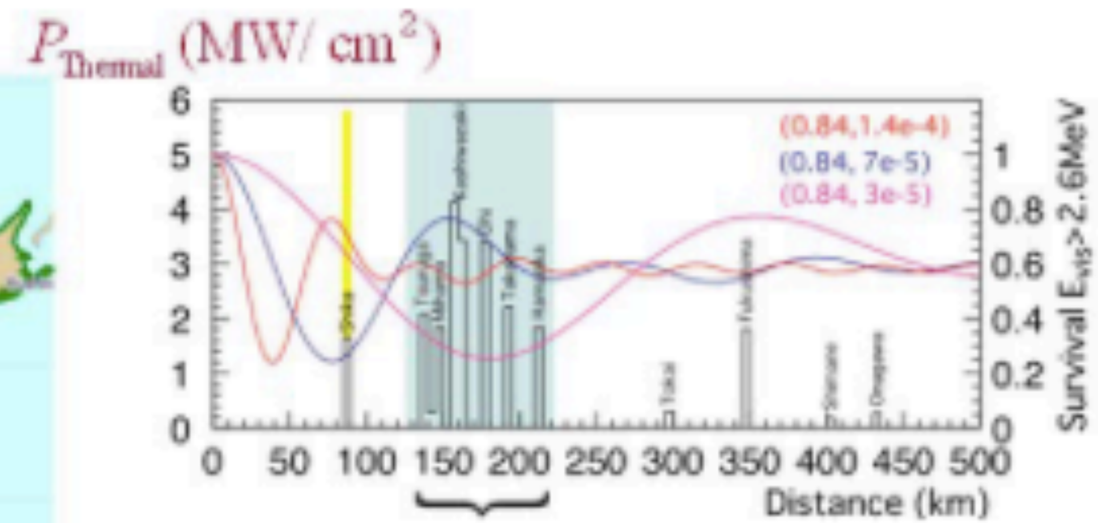
2 x KamLAND

$$\Delta m^2_{21}$$

How do we measure Δm^2_{21}

KamLAND:

Reactors near the KamLAND



80% of total contribution comes from 130~220km distance

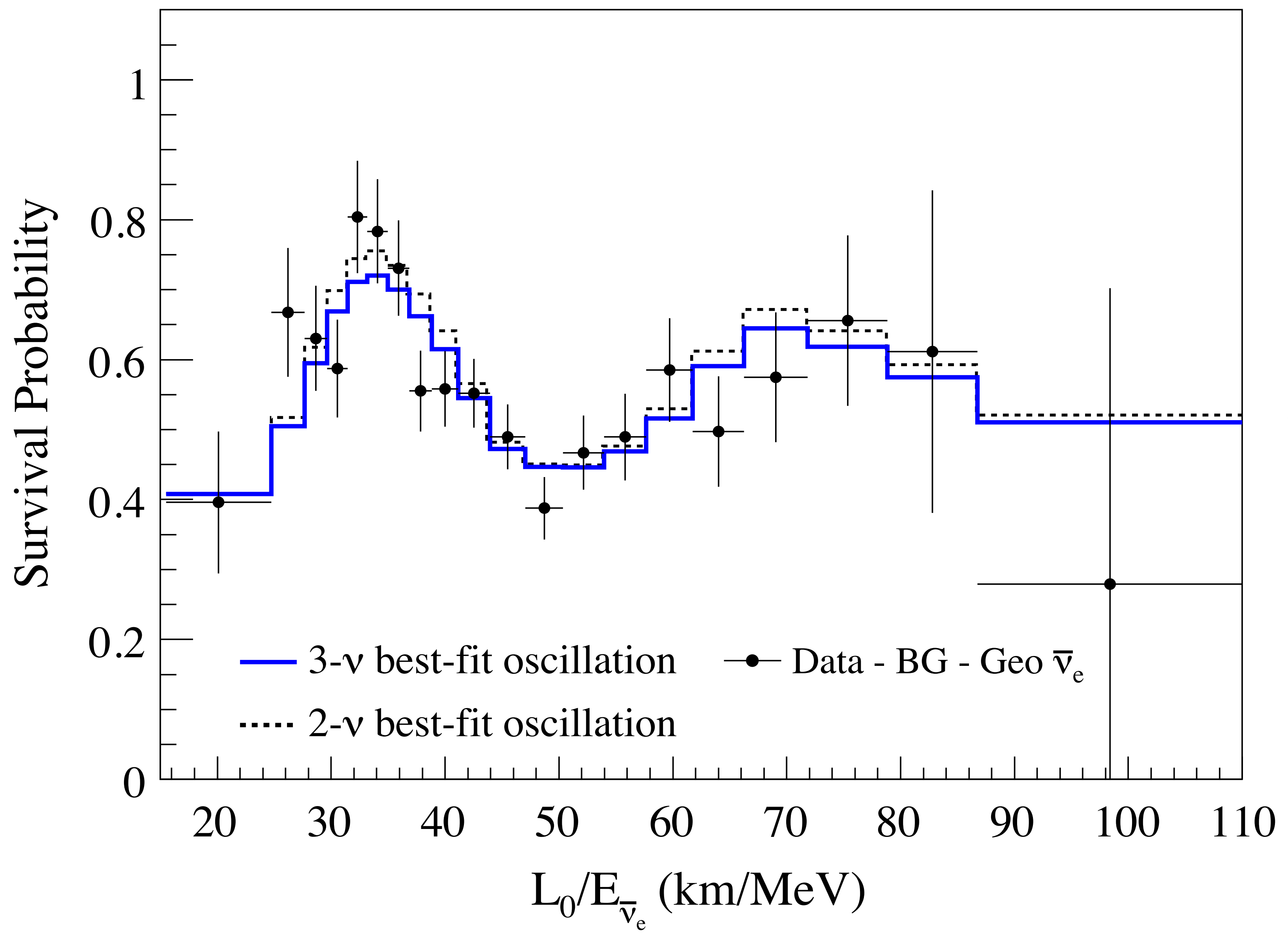
→ effective distance ~180km

Reactor neutrino flux, $\sim 6 \times 10^6/\mathrm{cm}^2/\mathrm{sec}$

~95.5% from Japan
~3% from Korea
(2nd result period)

Reactors in Taiwan have ~0.1% contribution.

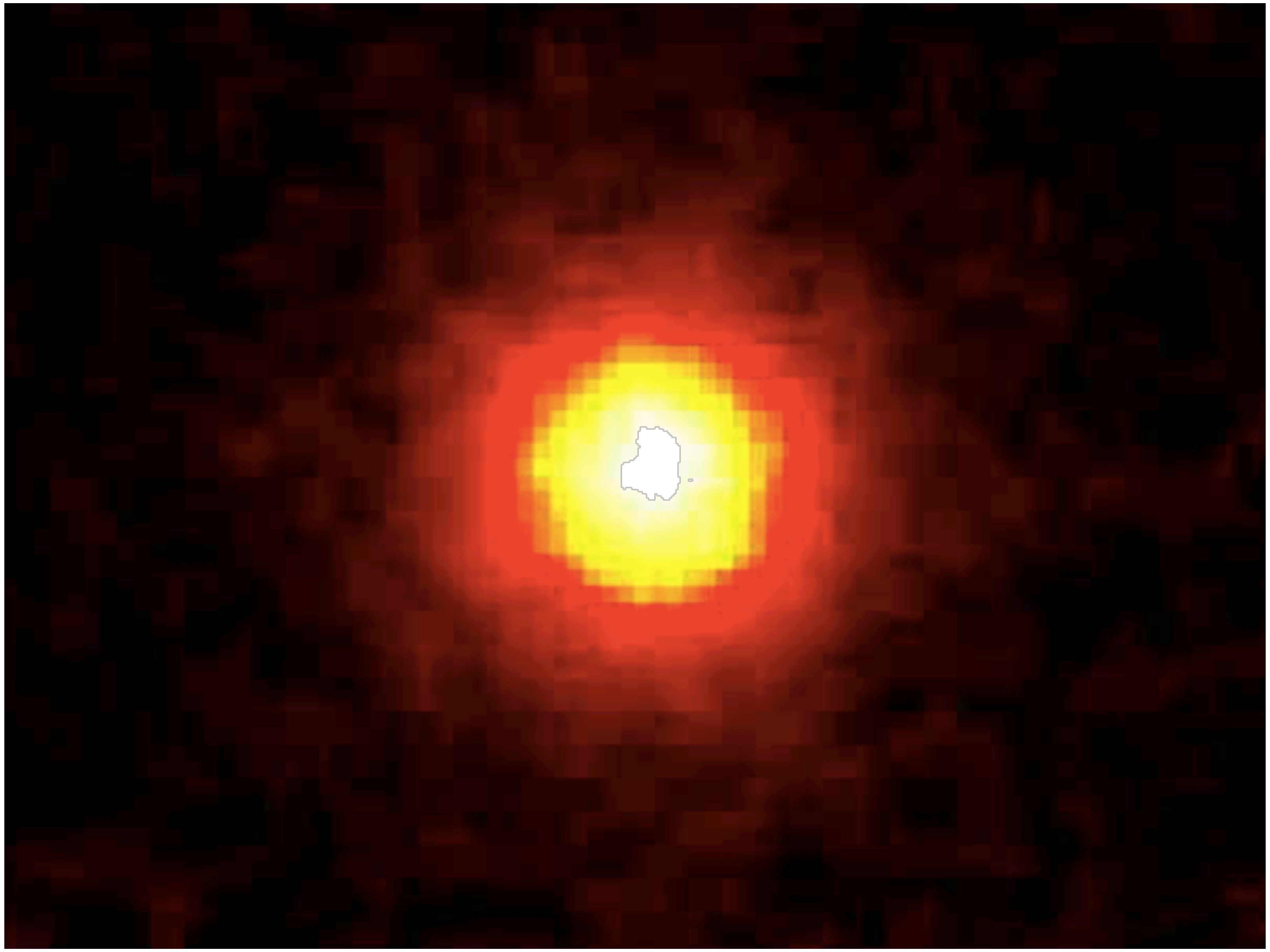
KamLAND:



Vacuum:
averaged osc
$\sim$ **68%** ν_1
$\sim$ **30%** ν_2
$\sim$ **2%** ν_3

$$\Delta m^2_{21} = 7.50\,^{+0.20}_{-0.20} \times 10^{-5}\ \text{eV}^2,$$

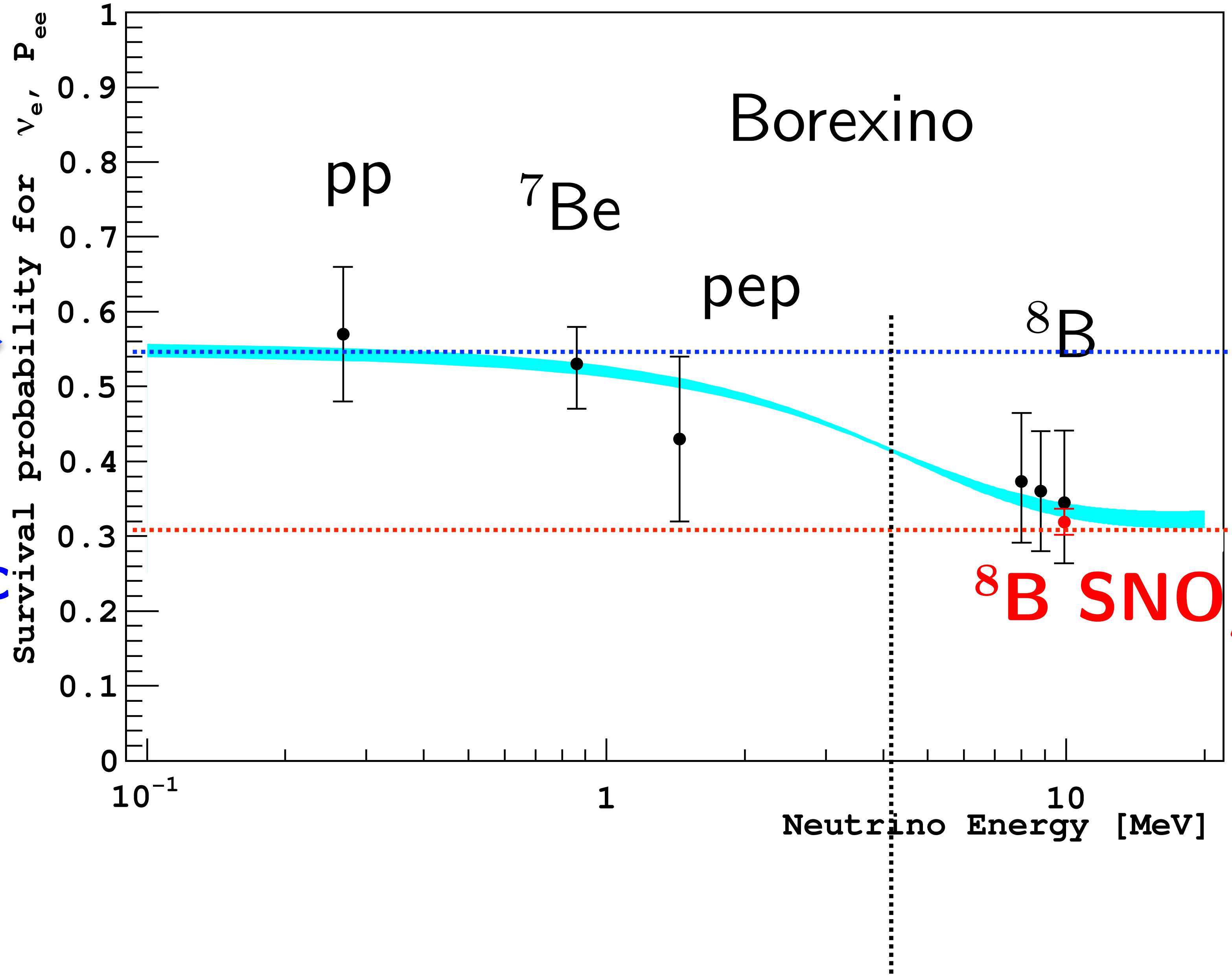
SuperK



$$\nu_? + e \rightarrow \nu + e$$

Which type of Neutrino dominates this image ?

Solar Neutrinos:



Vacuum: averaged osc

$\sim 68\%\ \nu_1$

$\sim 30\%\ \nu_2$

$\sim\ 2\%\ \nu_3$

MSW:

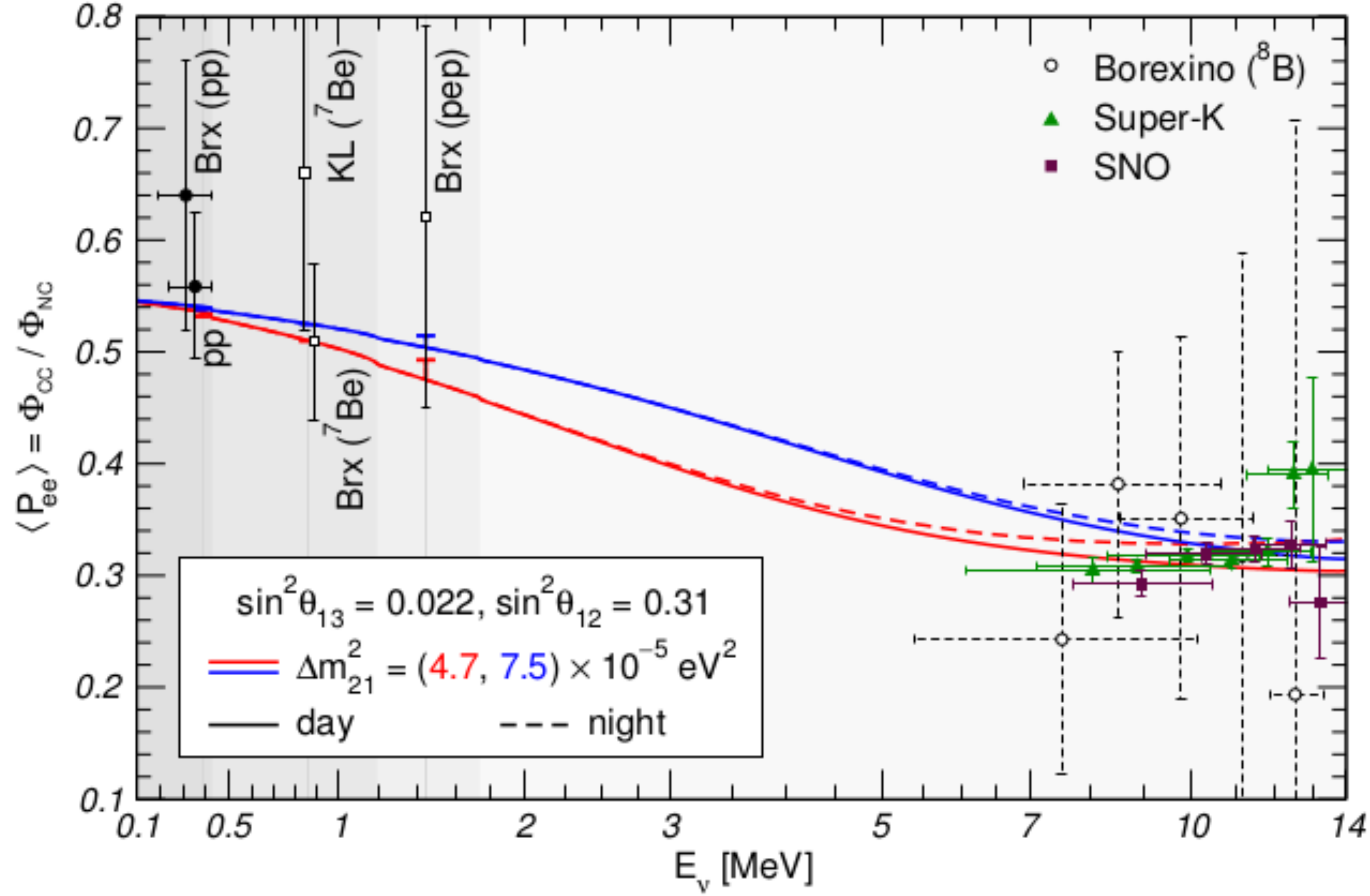
$> 90\%\ \nu_2$

matter effect

$$E_\nu = (\ \#\ )\Delta m^2_{21} \cos 2\theta_{12} / (\cos^2\theta_{13} 2\sqrt{2} G_F N_e)$$

Large Δm^2_{21} implies large E_ν at transition between Vac. and Matter dominated

Lack of observation of upturn at low E



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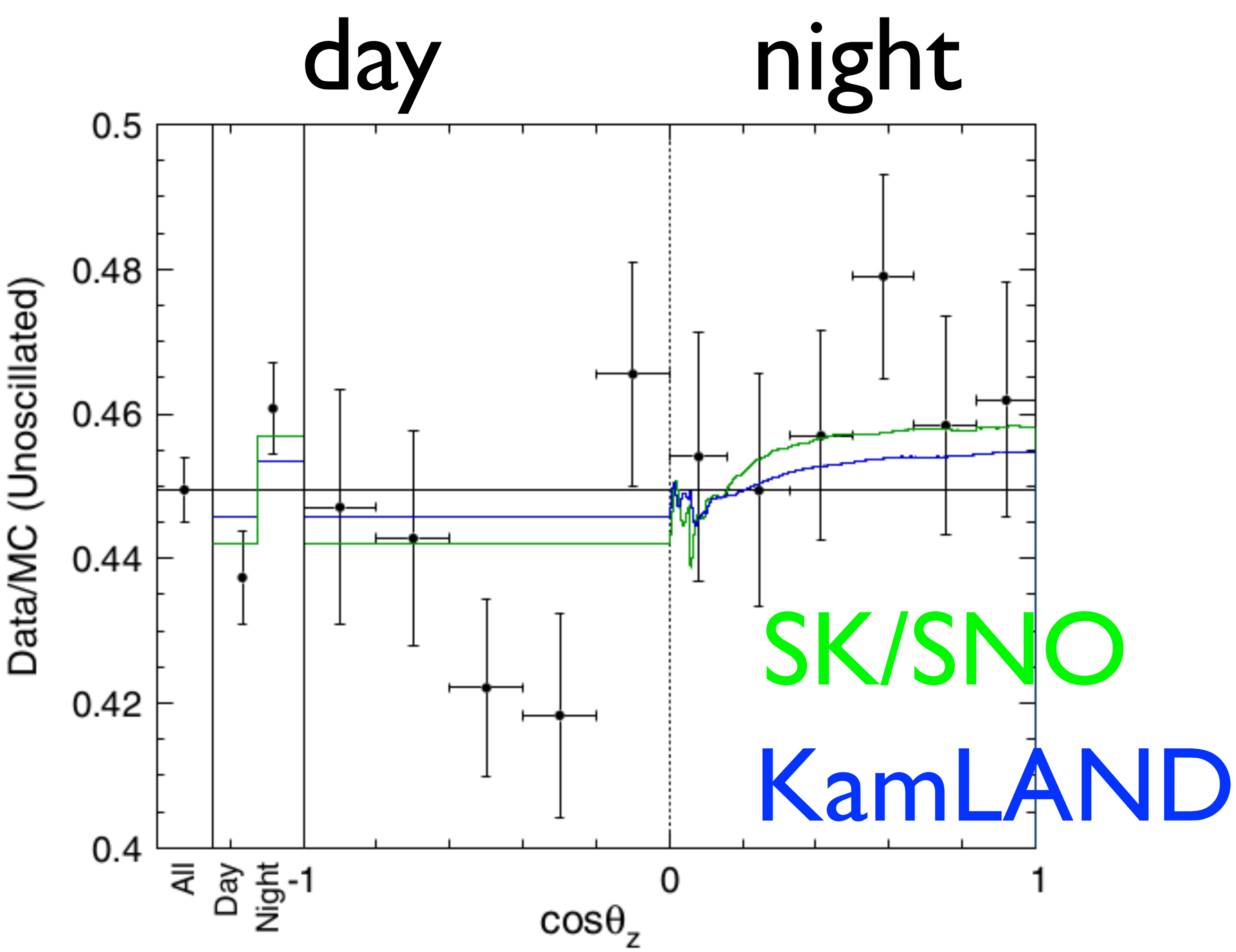
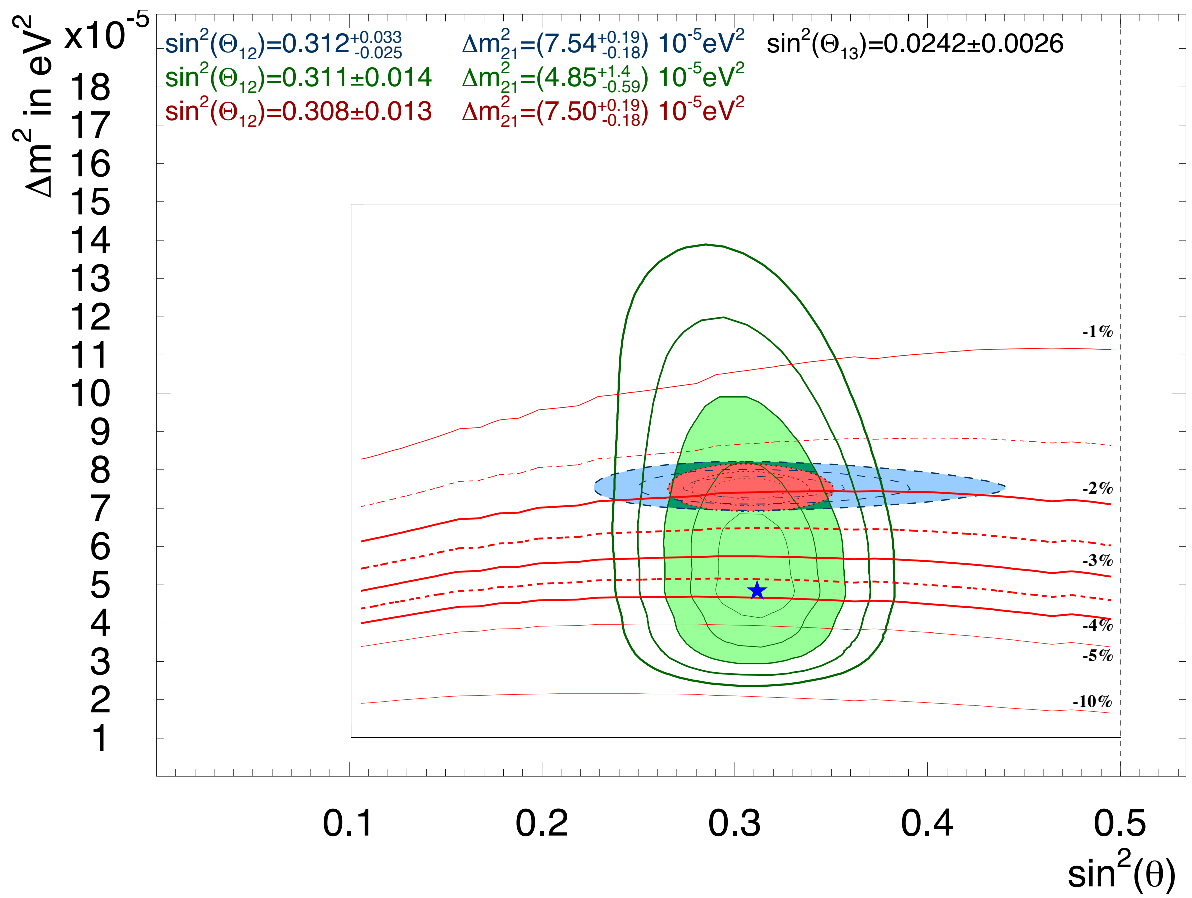
D/N asymmetry





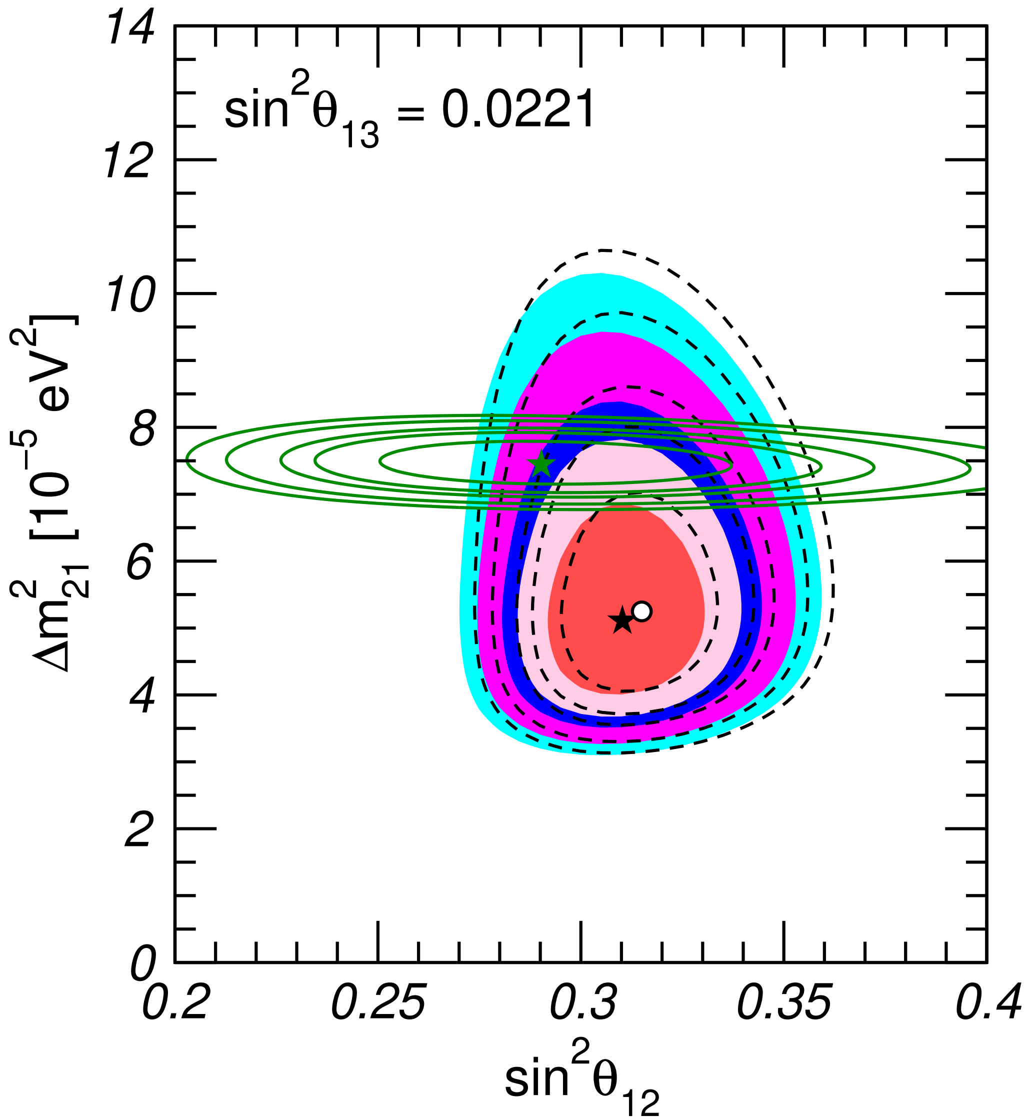
Phys. Rev. D94, 052010 (2016)

$$(D-N)/(D+N) = (\ \#\ )(\cos^2\theta_{13} 2\sqrt{2} G_F N_e^{\oplus})/\Delta m^2_{21} \cos 2\theta_{12}$$

Smaller Δm^2_{21} implies large D/N Asym.

Tension between KamLAND and SNO/SK

Nu-fit



KamLAND

$$\Delta m^2_{21} = 7.50\,^{+0.20}_{-0.20} \times 10^{-5}\ \mathrm{eV}^2,$$

SK/SNO

$$\Delta m^2_{21} = 5.1\,^{+1.3}_{-1.0} \times 10^{-5}\ \mathrm{eV}^2,$$

BSM explanations:

Scalar NSI

Ge + SP 1812.08376

3

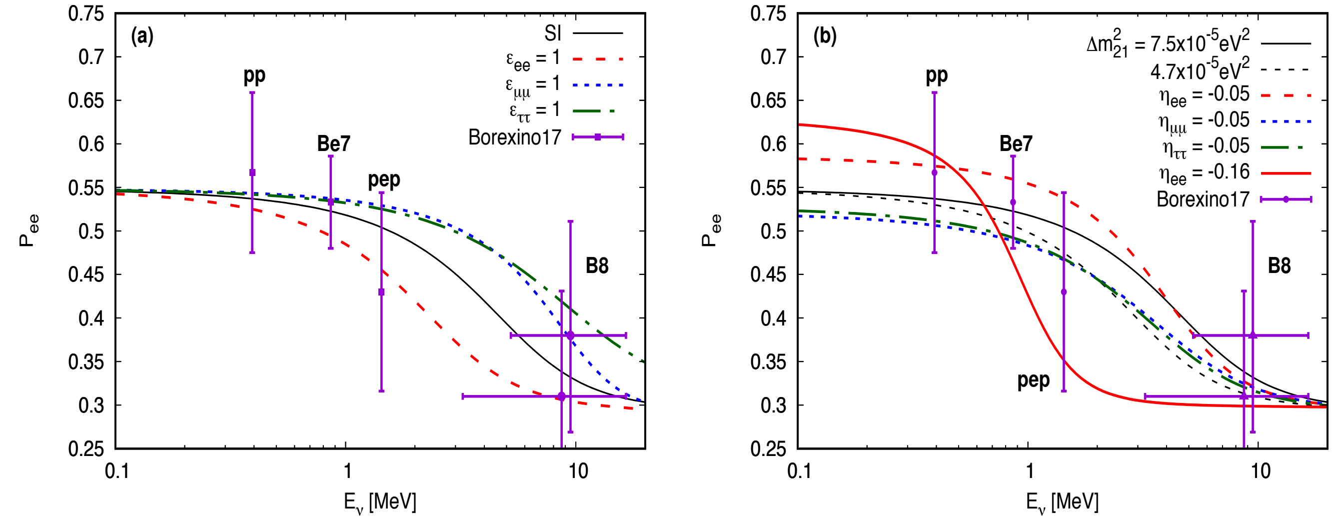


FIG. 2. The solar neutrino convertion probabilities with (a) the vector and (b) the scalar NSIs, together with the Borexino measurement [39] of the *pp*, ^{7}Be, and *pep* fluxes.

Steriles

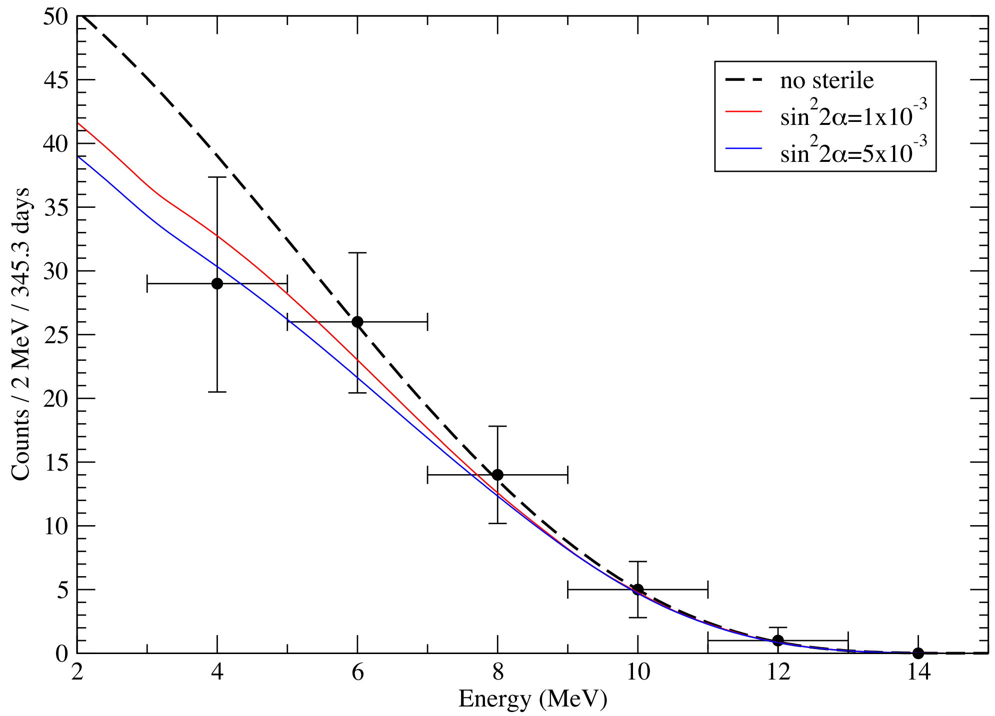
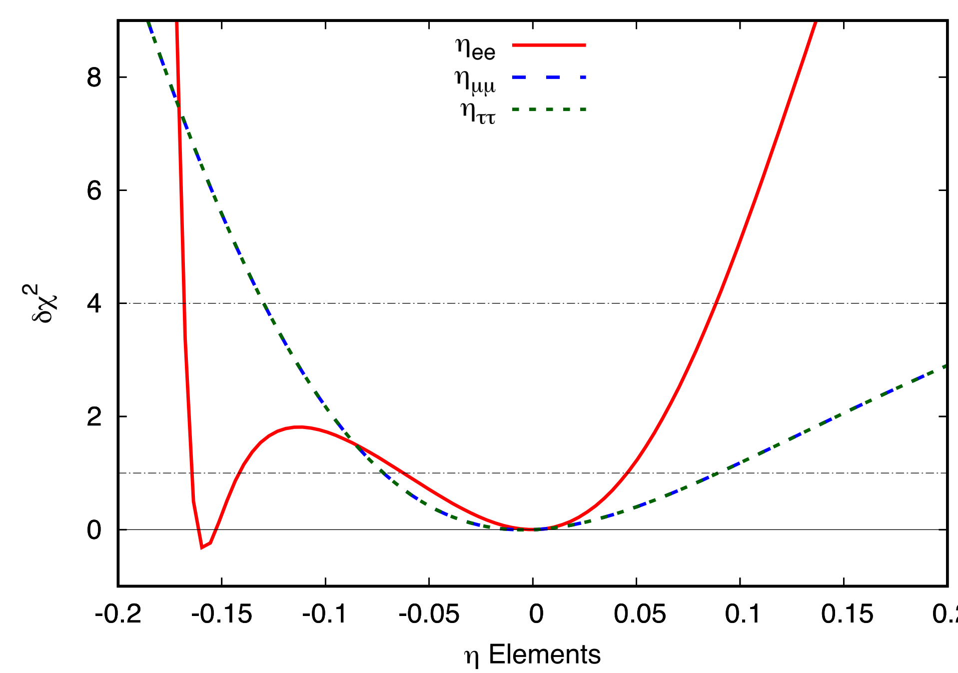


Figure 12: Prediction for $B-$neutrino spectrum at Borexino versus with experimental data [16]. The neutrino parameters and solar model are the same as in fig. 8.

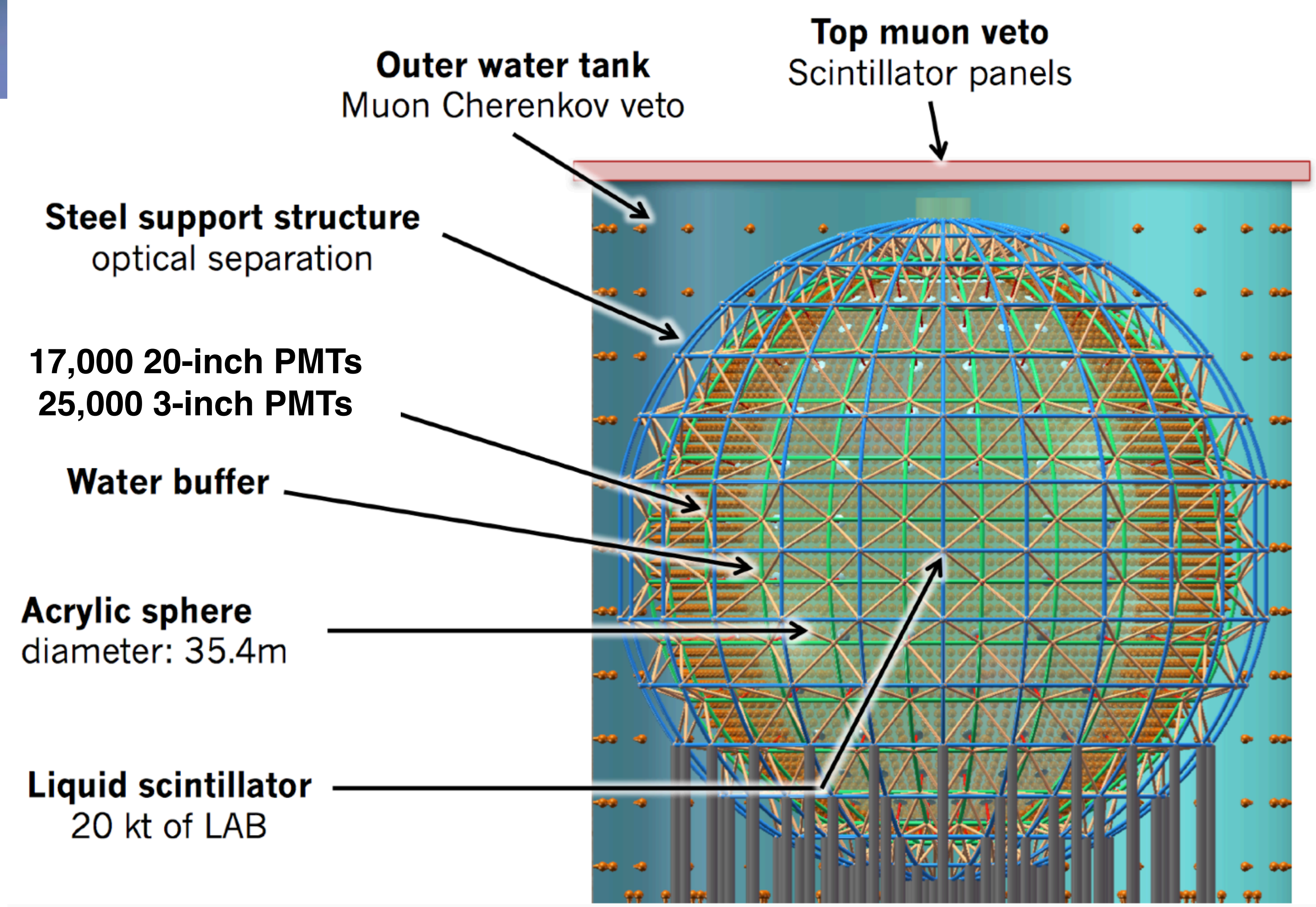


de Holanda + Smirnov
1012.5627

JUNO
circa 2025

JUNO

LS Detectors	Daya Bay	Borexino	KamLAND	JUNO
Target Mass	**20 t x 8**	**300 t**	**1 kt**	**20 kt**



Similar in concept to previous LS experiments, but much LARGER

In fact, JUNO will be the largest liquid scintillator (LS) detector so far in history!

JUNO precision ~2025

$$\sin^2\theta_{12},\ \Delta m^2_{21}\ \text{and}\ |\Delta m^2_{ee}|$$

0.5%

	Nominal	+ B2B (1%)	+ BG	+ EL (1%)	+ NL (1%)
$\sin^2\theta_{12}$	0.54%	0.60%	0.62%	0.64%	0.67%
Δm^2_{21}	0.24%	0.27%	0.29%	0.44%	0.59%
$\lvert\Delta m^2_{ee}\rvert$	0.27%	0.31%	0.31%	0.35%	0.44%

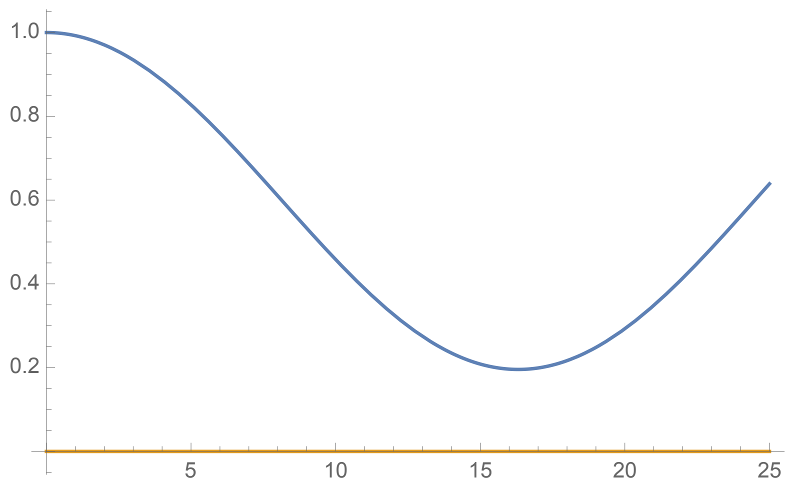
Table 3-2: Precision of $\sin^2\theta_{12}$, Δm^2_{21} and $|\Delta m^2_{ee}|$ from the nominal setup to those including additional systematic uncertainties. The systematics are added one by one from left to right.

$$\Delta m^2_{ee}(\text{NPZ}) \equiv \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

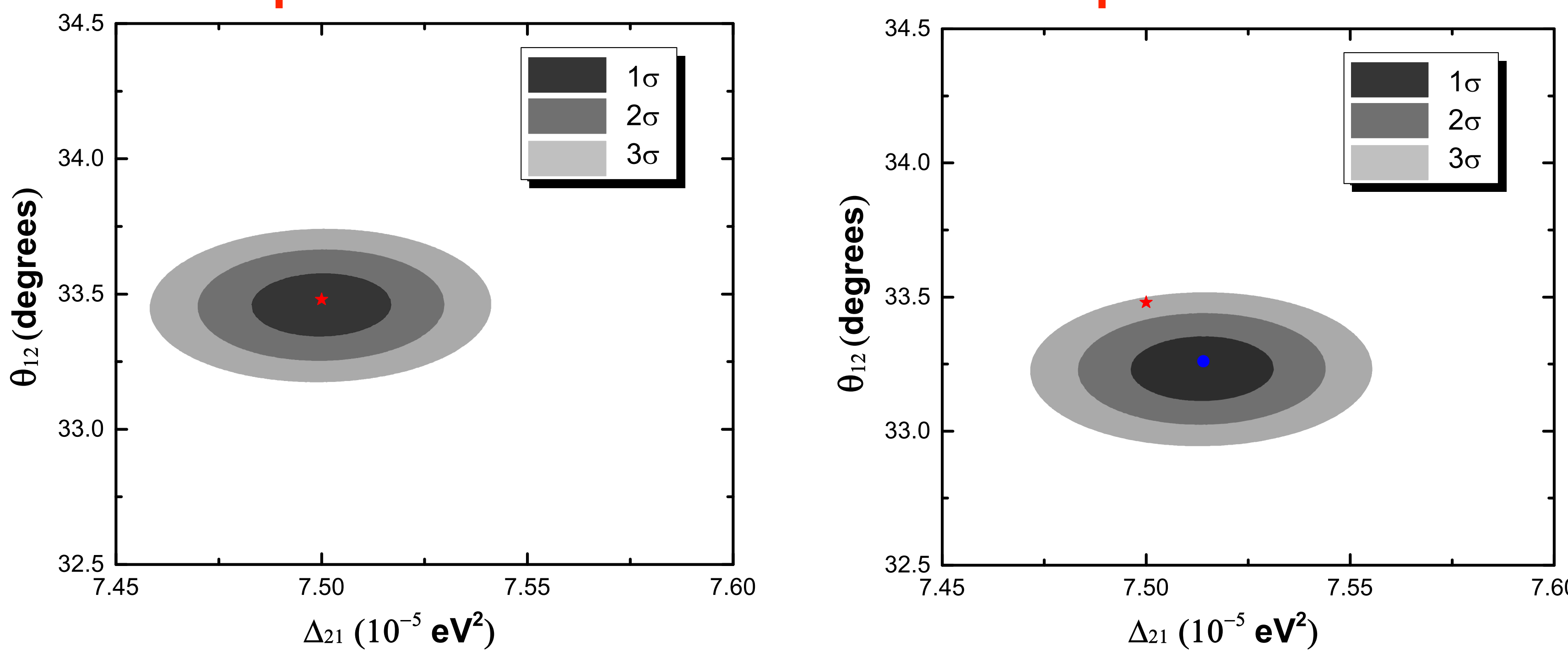
Matter Effects in JUNO

Li, Wang, Xing 1605.00900

$1 - P_{12}$



Matter Input/Matter Fit   Matter Input/Vacuum Fit



Shift 1σ in Δm^2_{21} and 3σ in θ_{12}

Size of shift unexplained in 1605.00900:

Khan, Nunokawa, SP upcoming 1810.?? or 1811.??

$\nu_e \to \nu_e$ and $\bar{\nu}_e \to \bar{\nu}_e$

REACTOR NEUTRINOS:

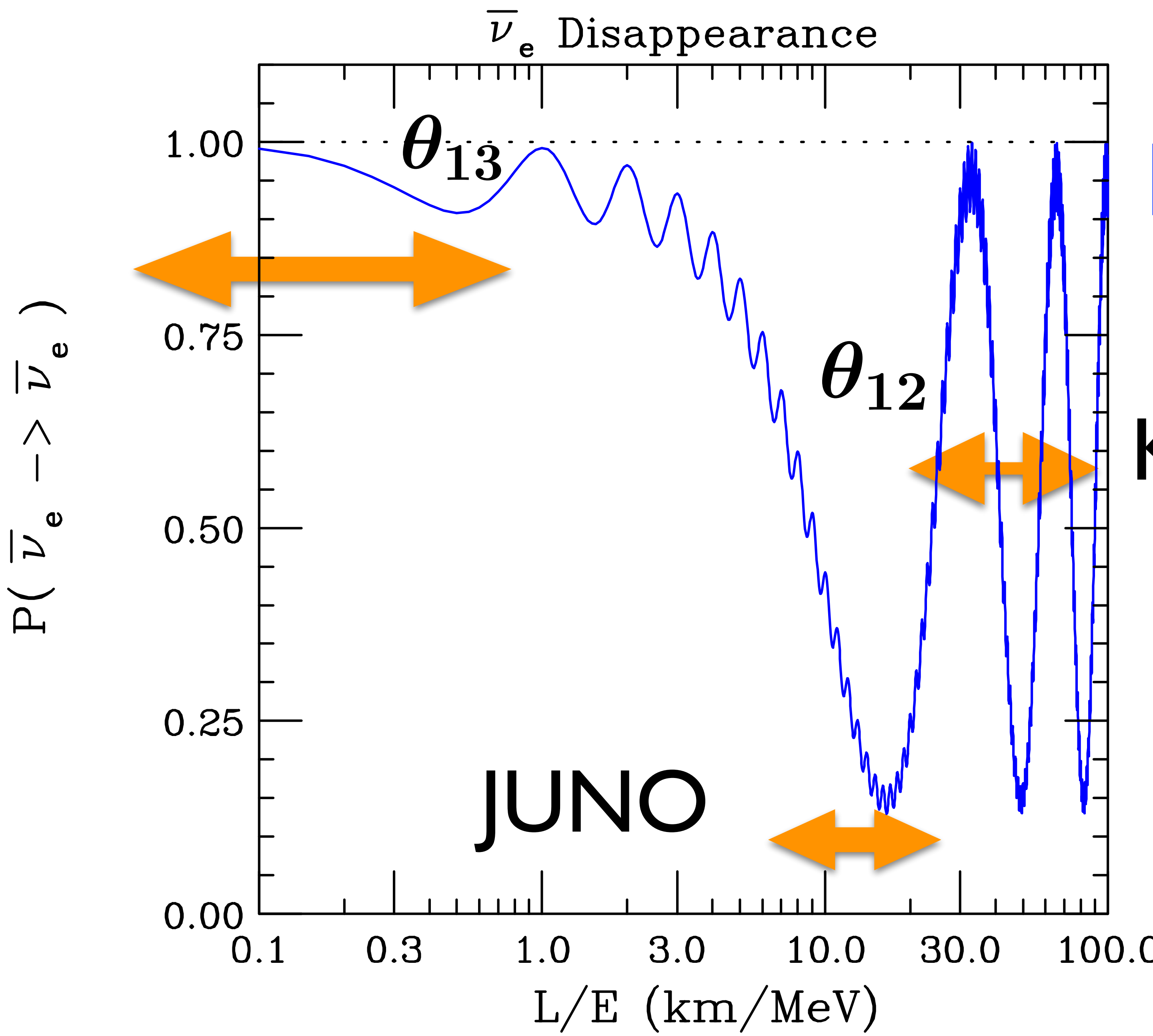
kinematic phase:

$$\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}$$

REACTOR NEUTRINOS:

$$\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}$$

Daya Bay
RENO
D-Chooz

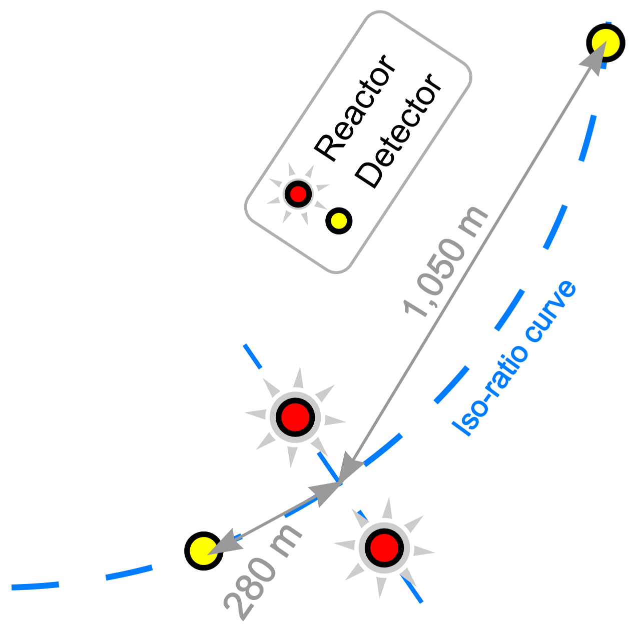


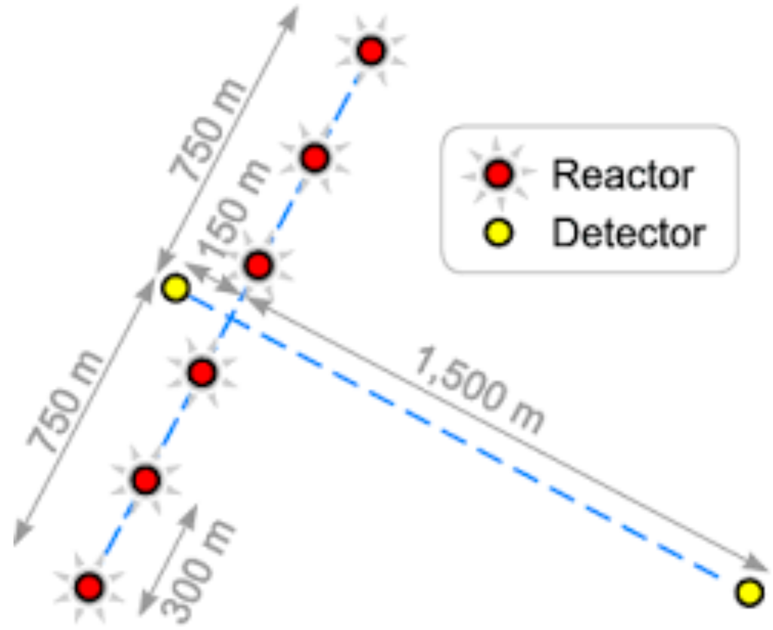
KamLAND

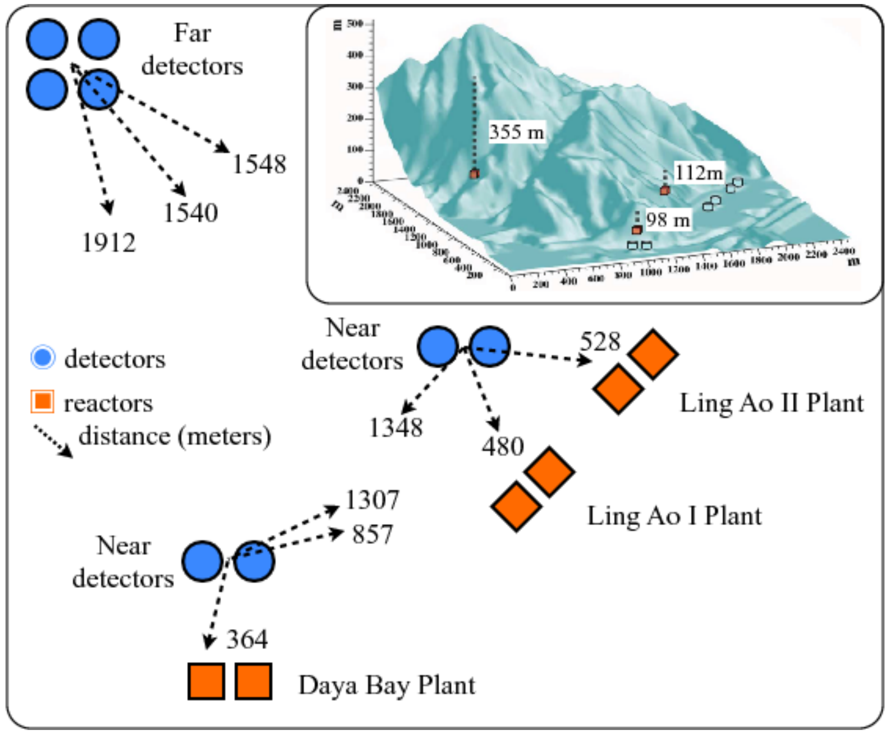
$\sin^2 2\theta_{13}$

$\cos 2\theta_{12} \sin^2 2\theta_{13}$
$\approx 0.4 \sin^2 2\theta_{13}$

Reactor θ_{13} Experiments





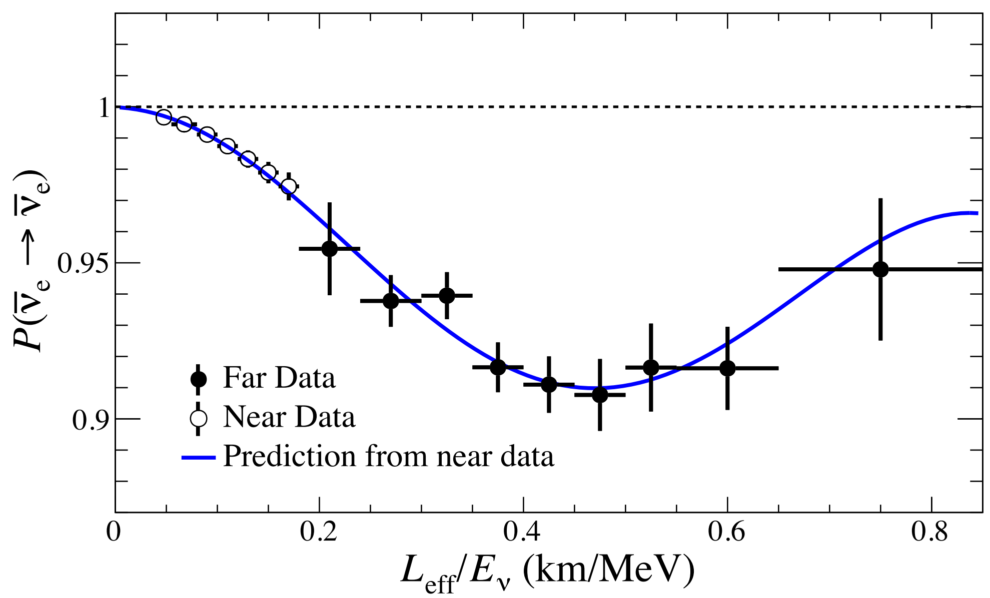


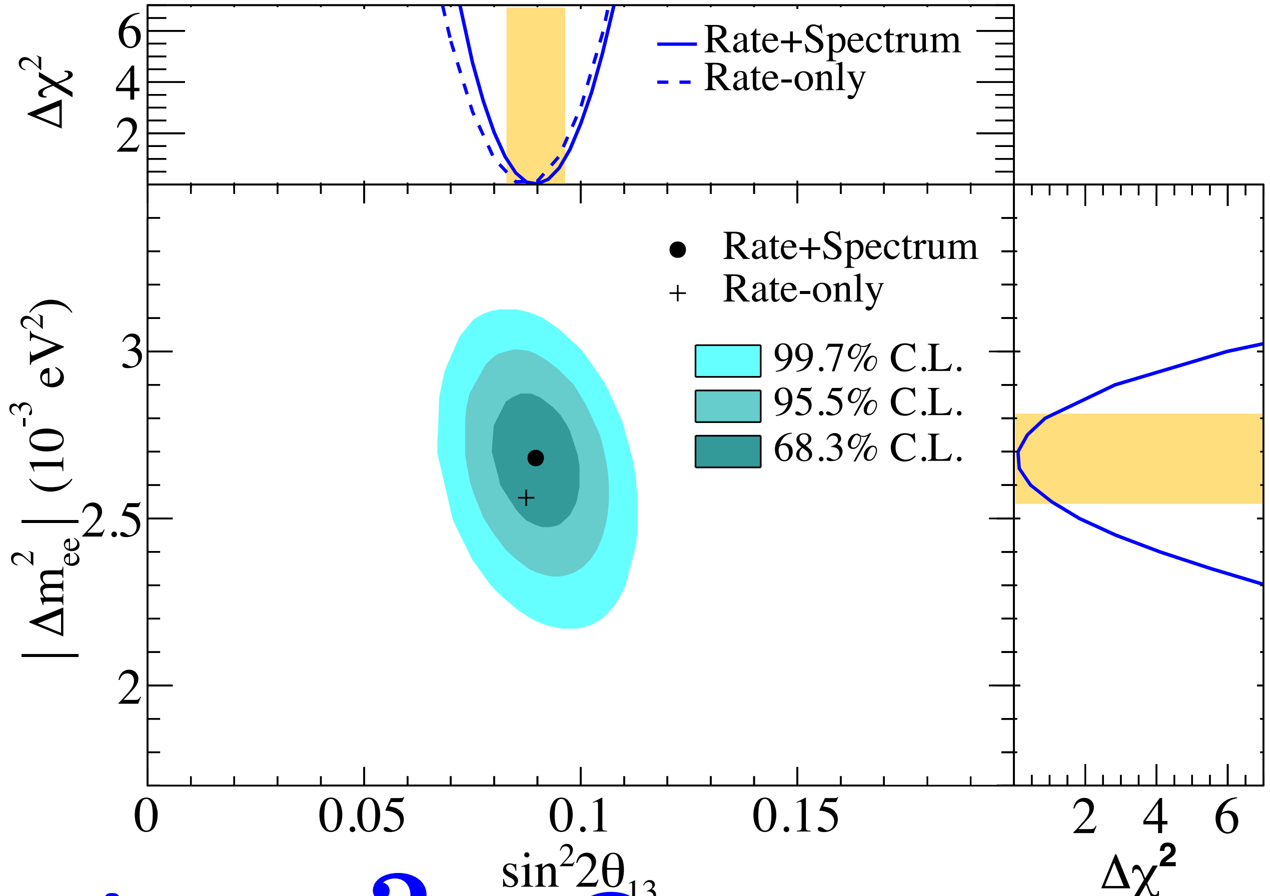
Double Chooz

RENO

Daya Bay

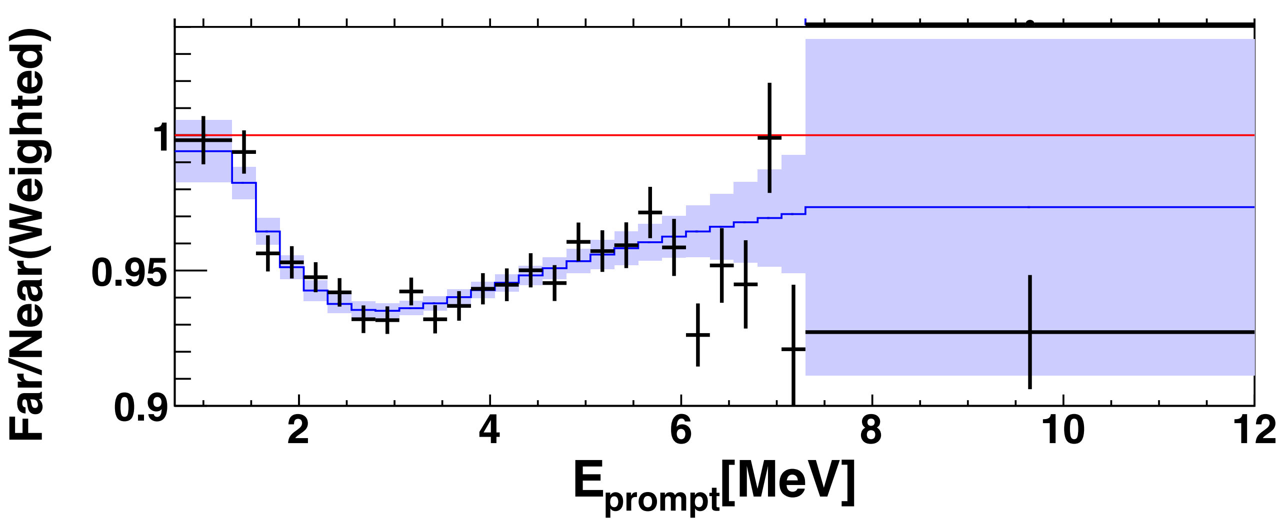
RENO 2200 days

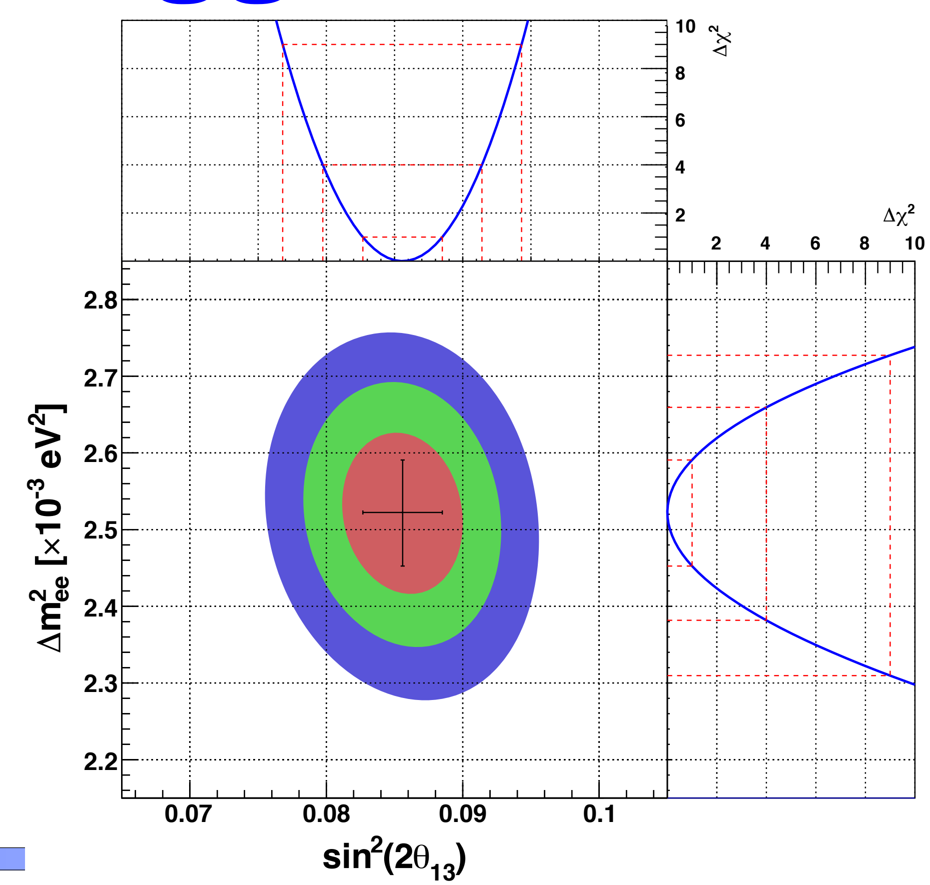




What is Δm^2_{ee} ?

Daya Bay 1958 days





~3%

Survival Probability:

$$P_{ee} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
$$- \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$
$$\approx 1 - (\cos^2\theta_{13}\ \sin 2\theta_{12}\,\Delta_{21})^2$$
$$- \sin^2 2\theta_{13}\sin^2\Delta_{ee}$$

$\sin\Delta_{21} \approx \Delta_{21}$ as $\Delta_{21} \ll \pi/6$

$$\sin^2\Delta_{ee} \approx \cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}$$

What makes a good Δm^2_{ee} ?

- good approx. for L/E $<$ 1 km/MeV
- Simply related to Δm^2_{31} and Δm^2_{32}
- Independent of L/E or "proper age" of the neutrino

$$\Delta m^2_{ee}(\mathrm{NPZ}) \equiv \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

$$= \Delta m^2_{31} - \sin^2\theta_{12}\Delta m^2_{21} = \Delta m^2_{32} + \cos^2\theta_{12}\Delta m^2_{21}$$

10^{-4} "ν_e average of Δm^2_{31} and Δm^2_{32}" hep-ph/0503283

$$\Delta m^2_{ee}(\mathrm{DB1}) \equiv \left(\tfrac{4E}{L}\right)\arcsin\sqrt{\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta m^2_{32}}$$

exact 1310.6732, 1505.03456v1

$$\Delta m^2_{ee}(\mathrm{DB2}) \quad \equiv \quad \Delta m^2_{32} + \left(\frac{2E}{L}\right)\arctan\left(\frac{\sin 2\Delta_{21}}{\cos 2\Delta_{21} + \tan^2\theta_{12}}\right)$$

10^{-4}

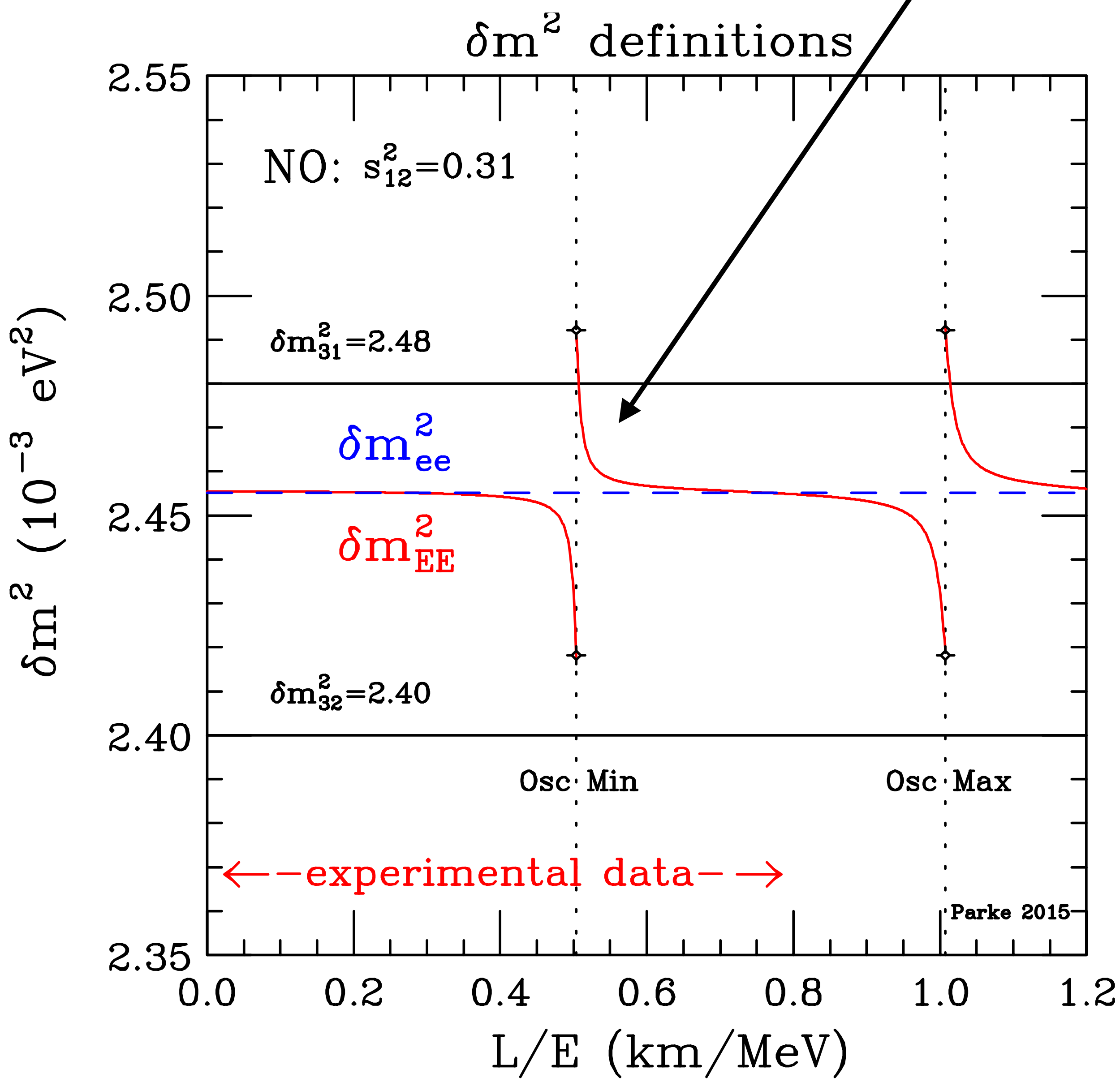
1505.03456v2,1809.02261

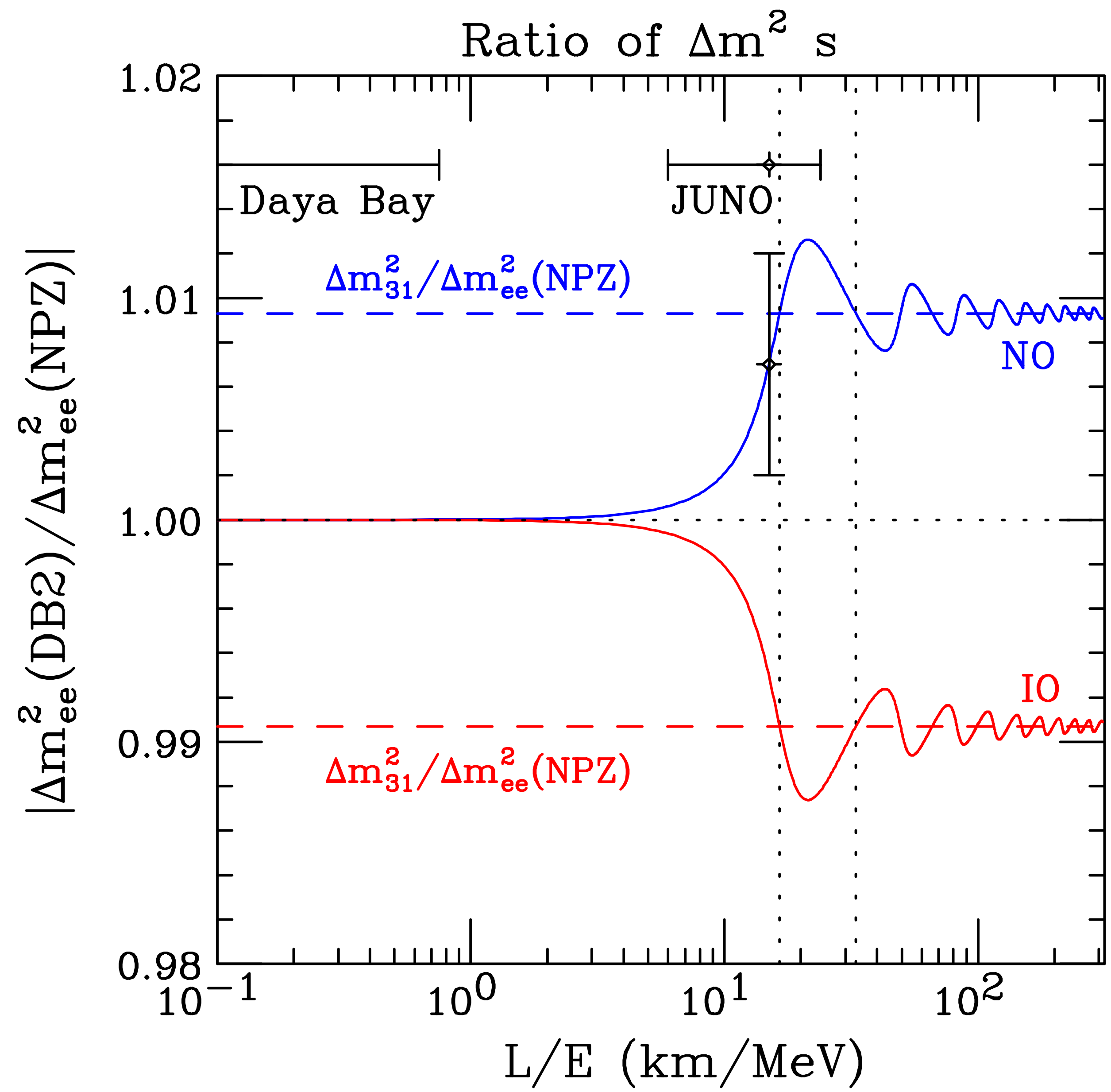
$$\Delta m^2_{ee}(\mathrm{SP}) \equiv \sqrt{\cos^2\theta_{12}(\Delta m^2_{31})^2 + \sin^2\theta_{12}(\Delta m^2_{32})^2} \approx \Delta m^2_{ee}(\mathrm{NPZ})\left[1 + \frac{1}{2}s^2_{12}c^2_{12}\left(\frac{\Delta m^2_{21}}{\Delta m^2_{ee}}\right)^2\right]$$

10^{-4} 1601.07464

$$\Delta m^2_{ee}(\mathrm{DB1}) \equiv \left(\frac{4E}{L}\right) \arcsin \sqrt{\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta m^2_{32}}$$

$$\Delta m^2_{ee}(\mathrm{DB2}) \equiv \Delta m^2_{32} + \left(\frac{2E}{L}\right) \arctan\left(\frac{\sin 2\Delta_{21}}{\cos 2\Delta_{21} + \tan^2\theta_{12}}\right)$$





1310.6732, 1505.03456v1

1903.00148

Can Short Baseline Reactor Neutrinos
say anything about

$$\Delta m^2_{21}$$

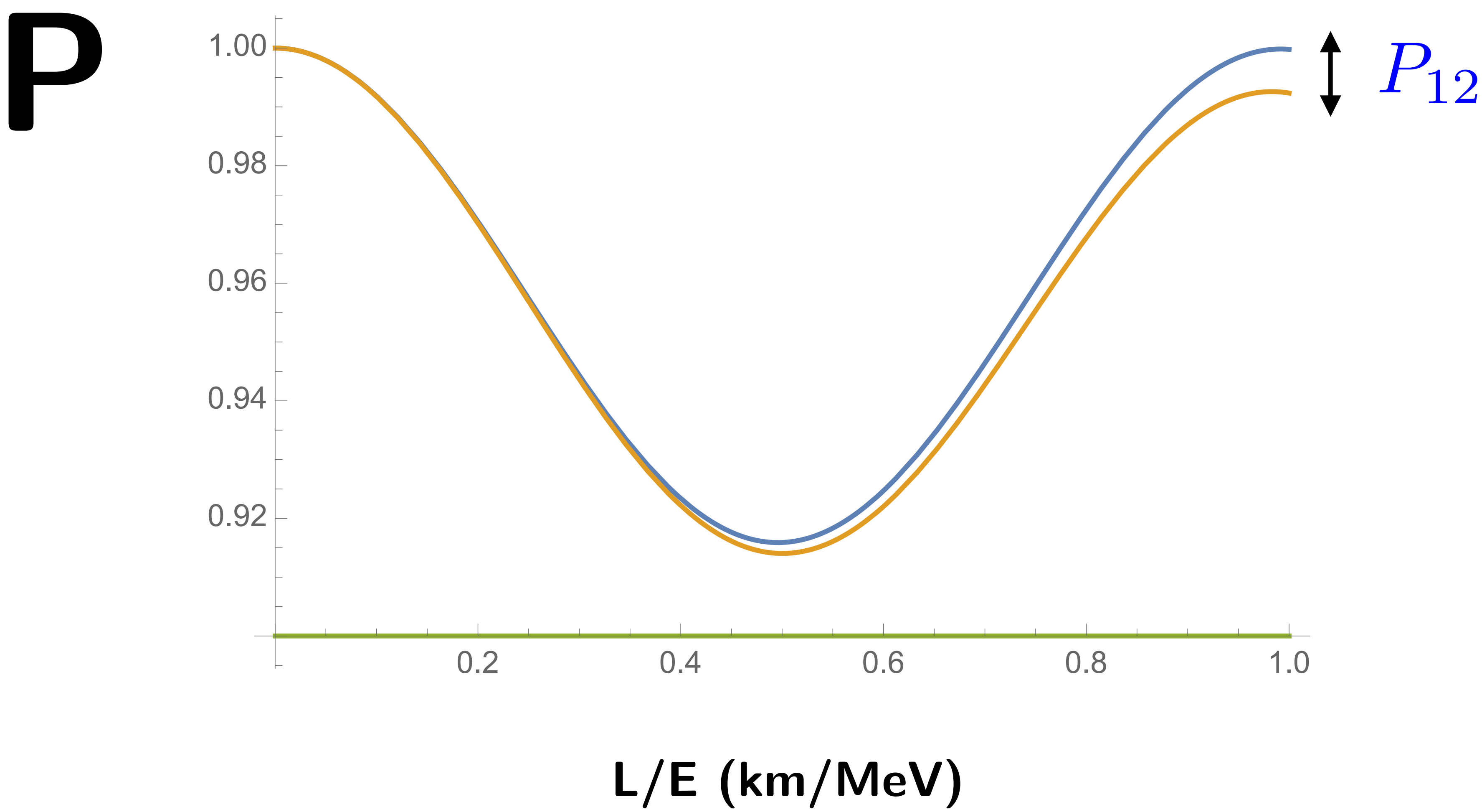
S.H. Seo and SP arXiv:1808.09150

$$\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}$$

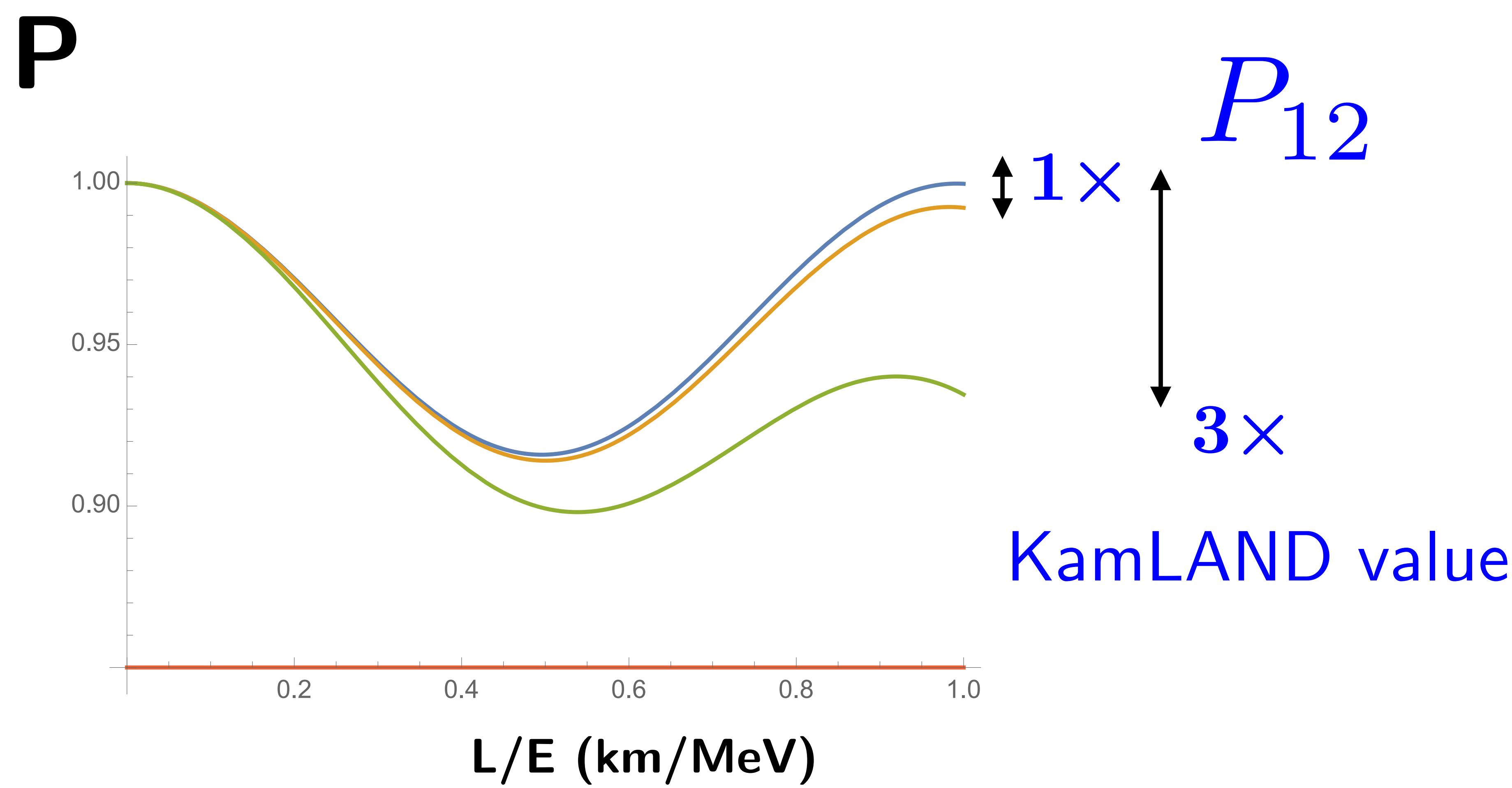
$$P_{ee} = 1 - P_{13} - P_{12}$$

$$P_{13} = \sin^2 2\theta_{13} \sin^2 \Delta_{ee} \qquad (< 0.1)$$

$$P_{12} = (\cos^2\theta_{13} \, \sin 2\theta_{12} \, \Delta_{21})^2 \qquad (< 0.01)$$



Dependence on Solar Parameters:

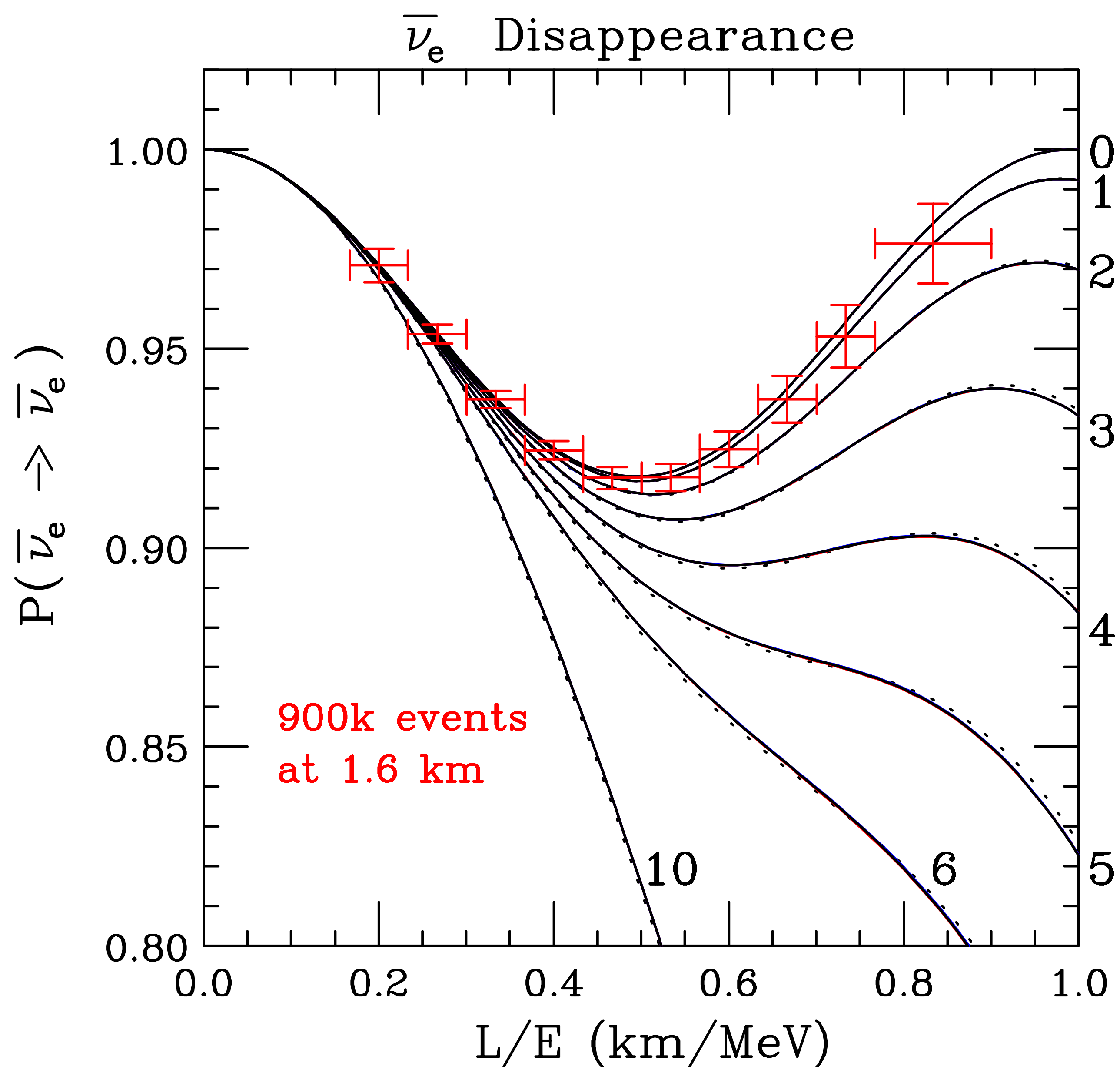


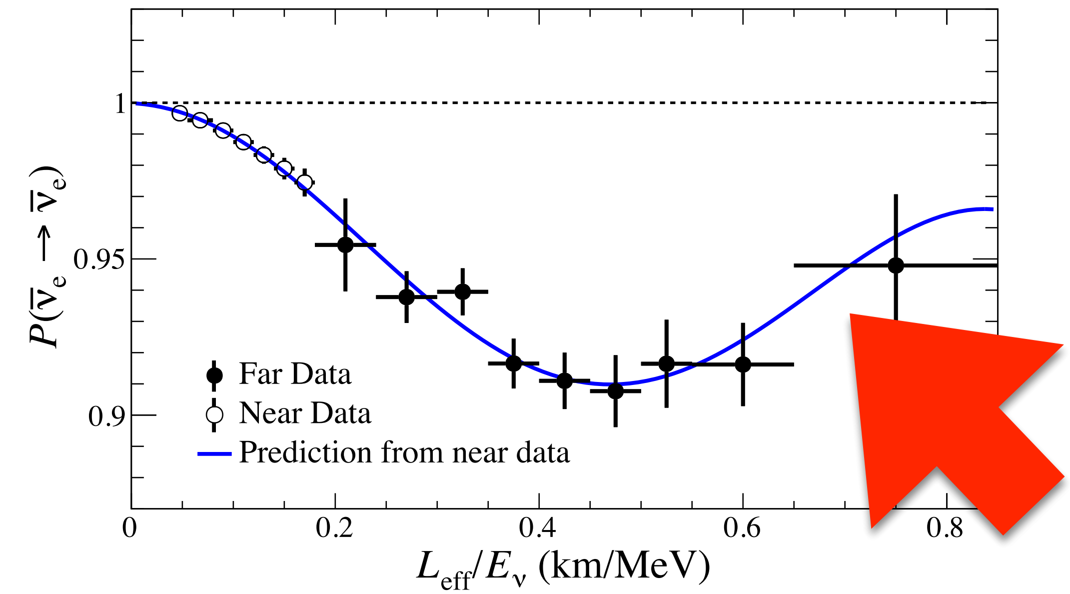
$$P_{13} \approx 0.08 \sin^2\left(\frac{\pi}{2}\left(\frac{L/E}{0.5\,\mathrm{km/MeV}}\right)\right)$$

$$P_{12} \approx 0.002\left(\frac{L/E}{0.5\,\mathrm{km/MeV}}\right)^2\left(\frac{\Delta m^2_{21}}{7.5\times 10^{-5}\,\mathrm{eV}^2}\right)^2$$

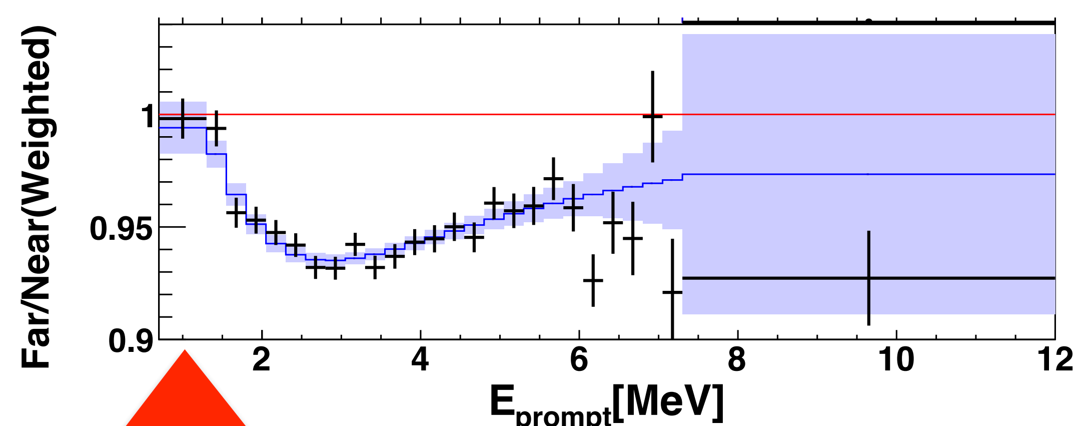
If Δm^2_{21} is 3 times bigger, P_{12} is 9 times larger !

RENO





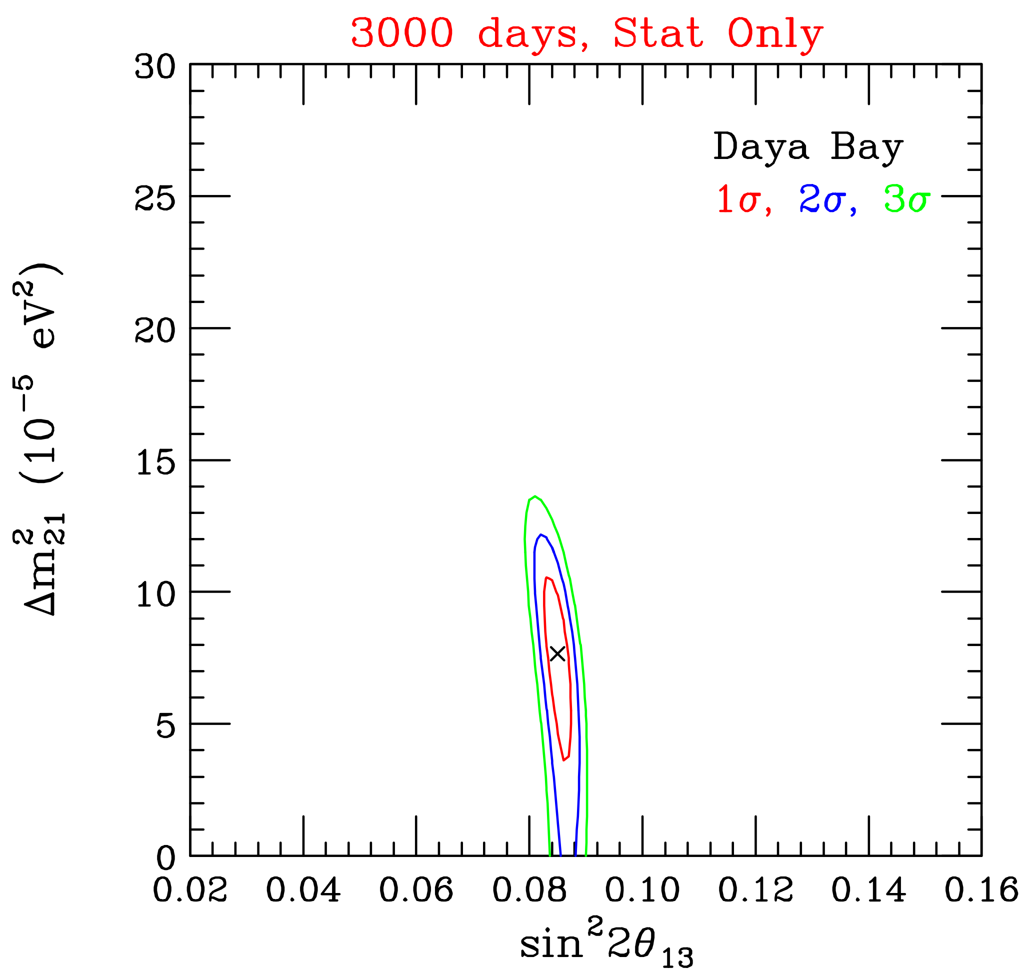
Daya Bay

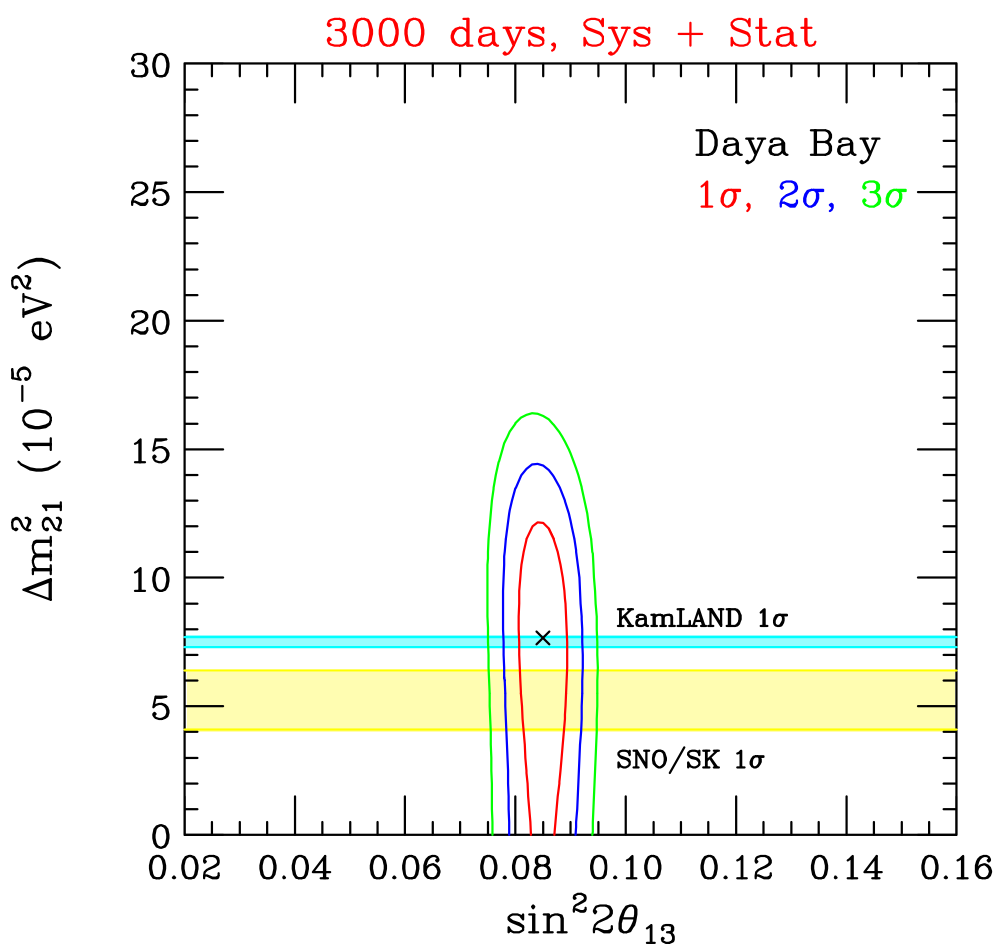


1 - 10 KamLAND

$$\Delta m^2_{21}$$

Simulation





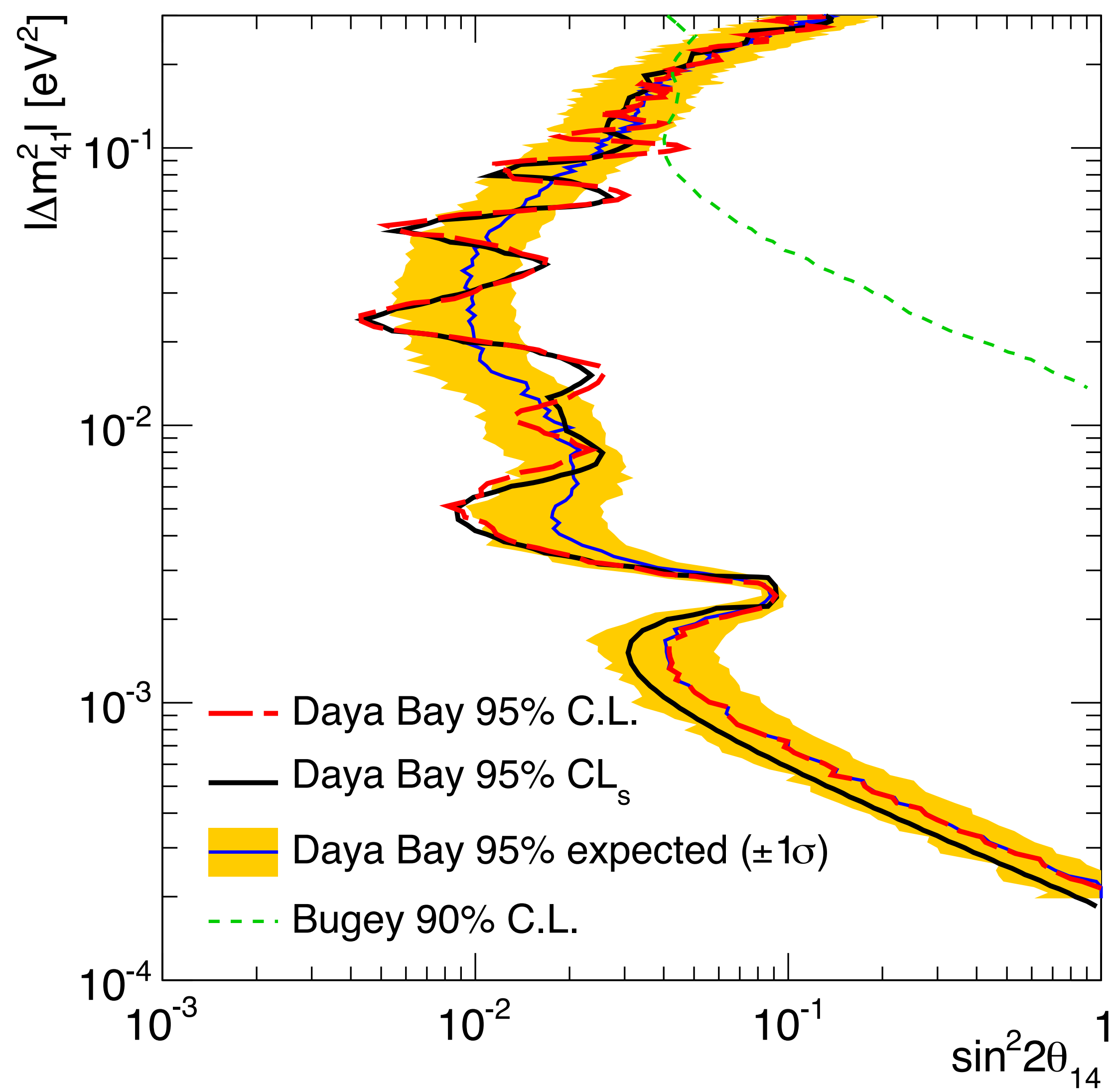
L/E $\sim$ 0.5 km/MeV compared to KamLAND L/E $\sim$ 50 km/MeV

T2K is at 0.5 km/MeV

Daya Bay
Sterile Neutrino Search

$$\approx 1 - \sin^2 2\theta_{14} \sin^2 \Delta_{41} - \sin^2 2\theta_{13} \sin^2 \Delta_{31}.$$

1607.01174
404 days



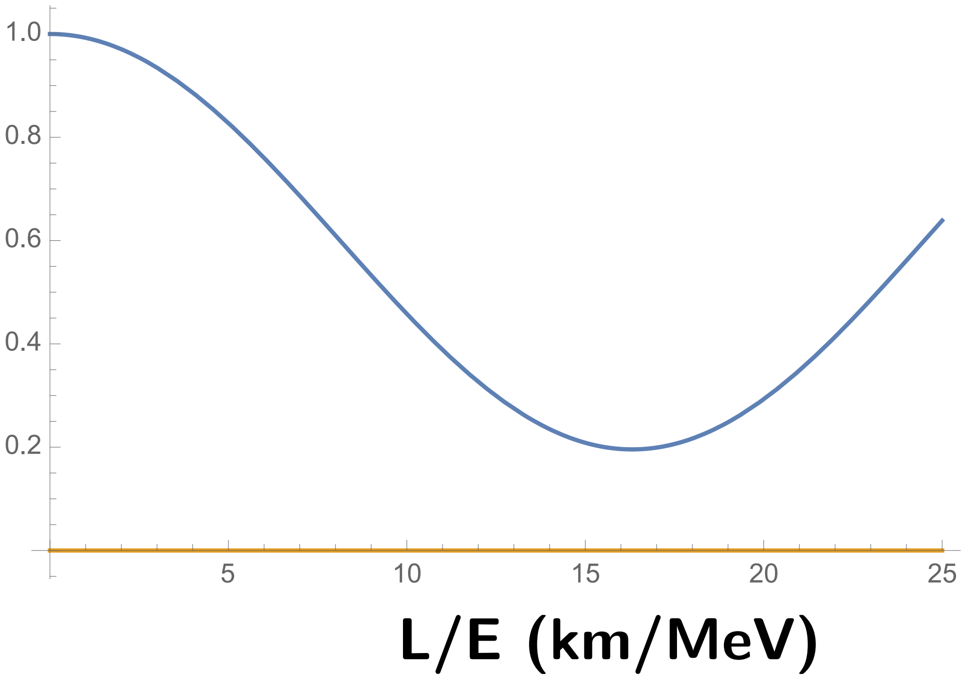
$\mathbf{3}\times$

KamLAND value

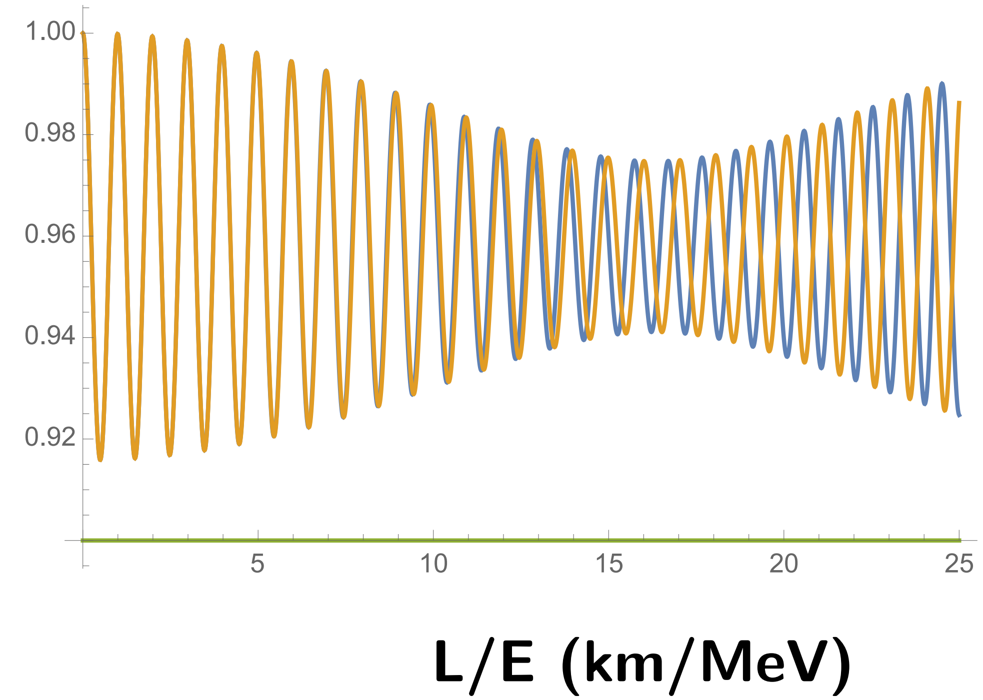
Reinterpretation !

JUNO and the Mass Ordering:

$1 - P_{12}$

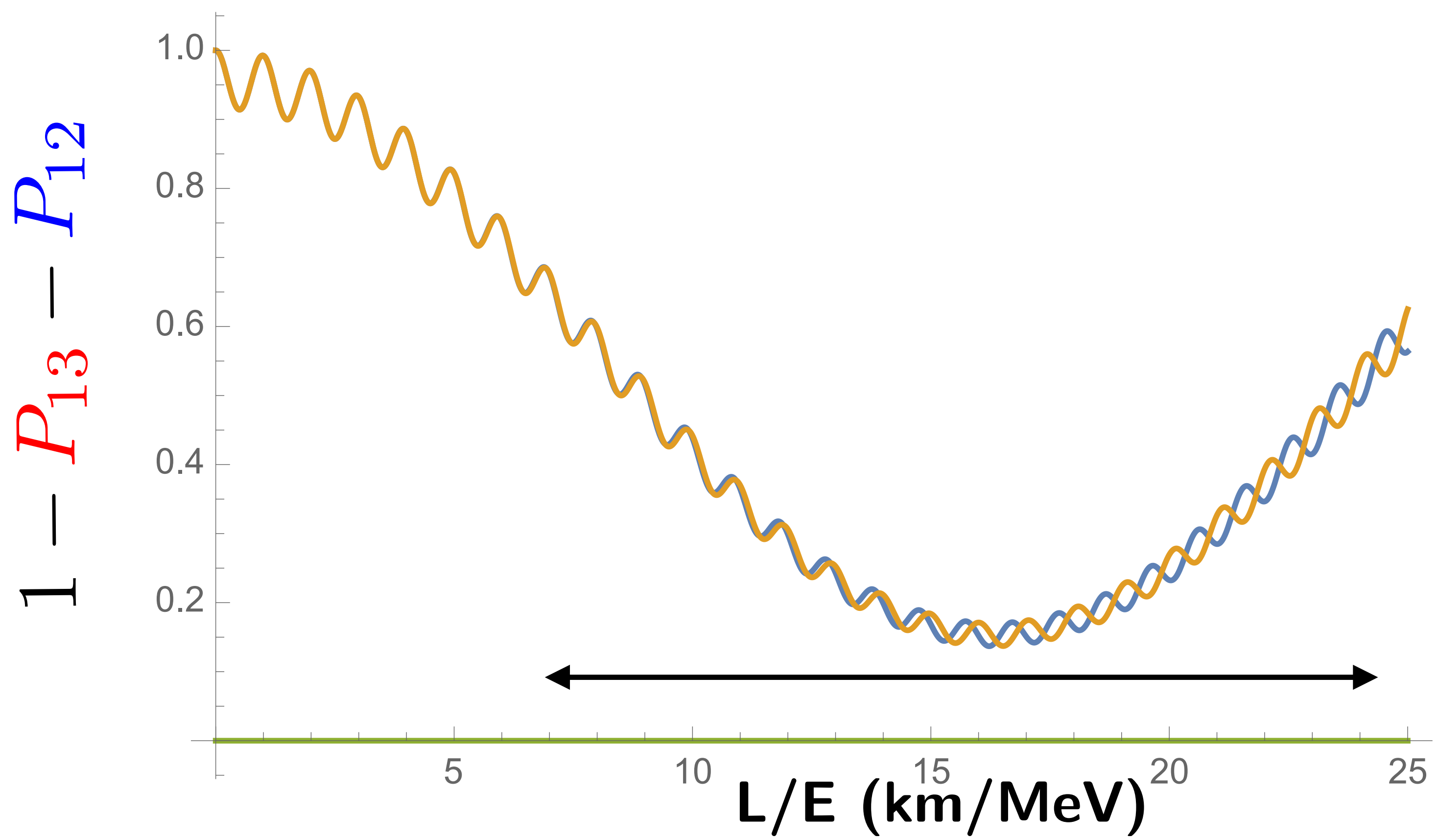


$1 - P_{13}$



NO

IO

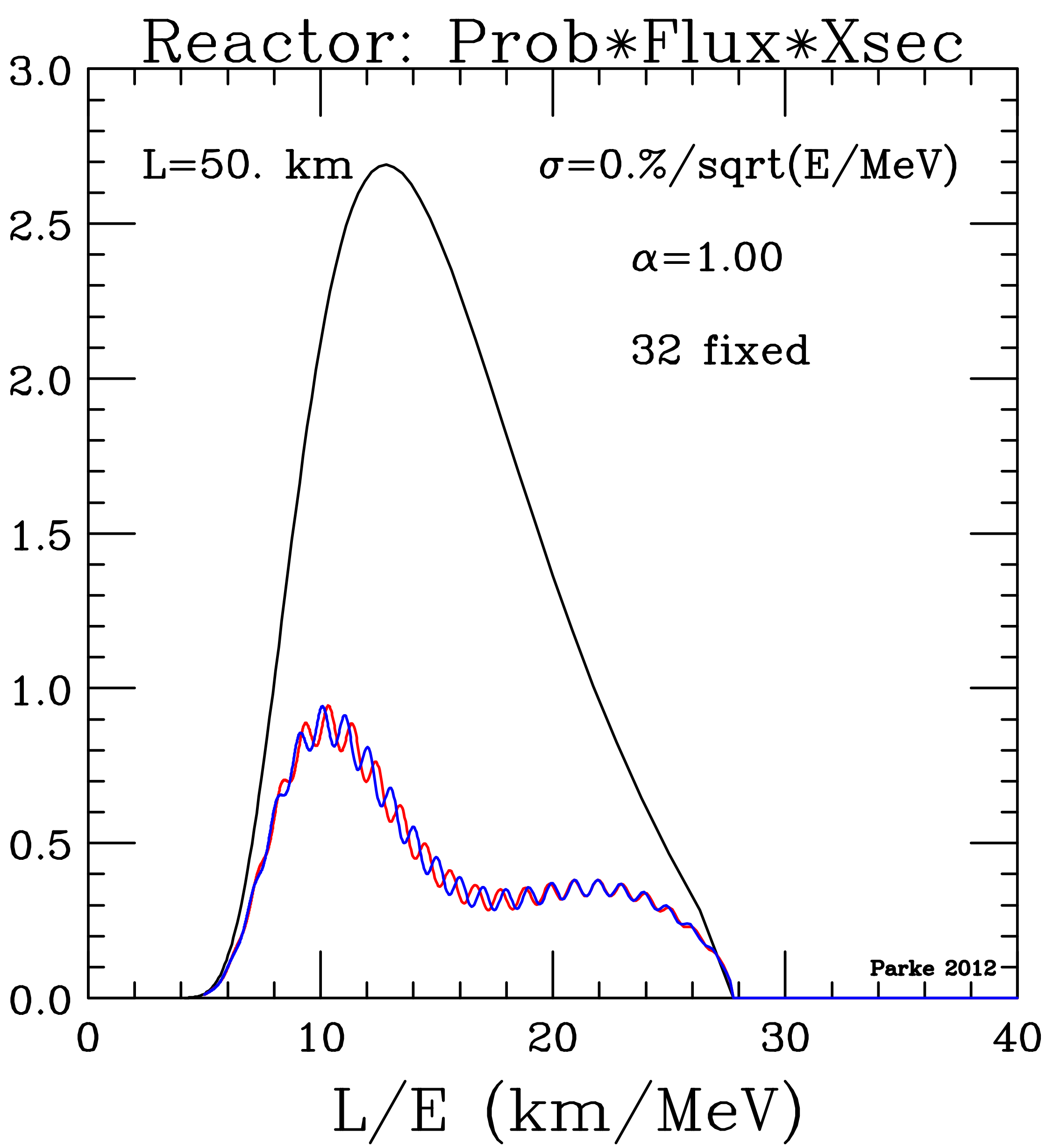


NO

IO

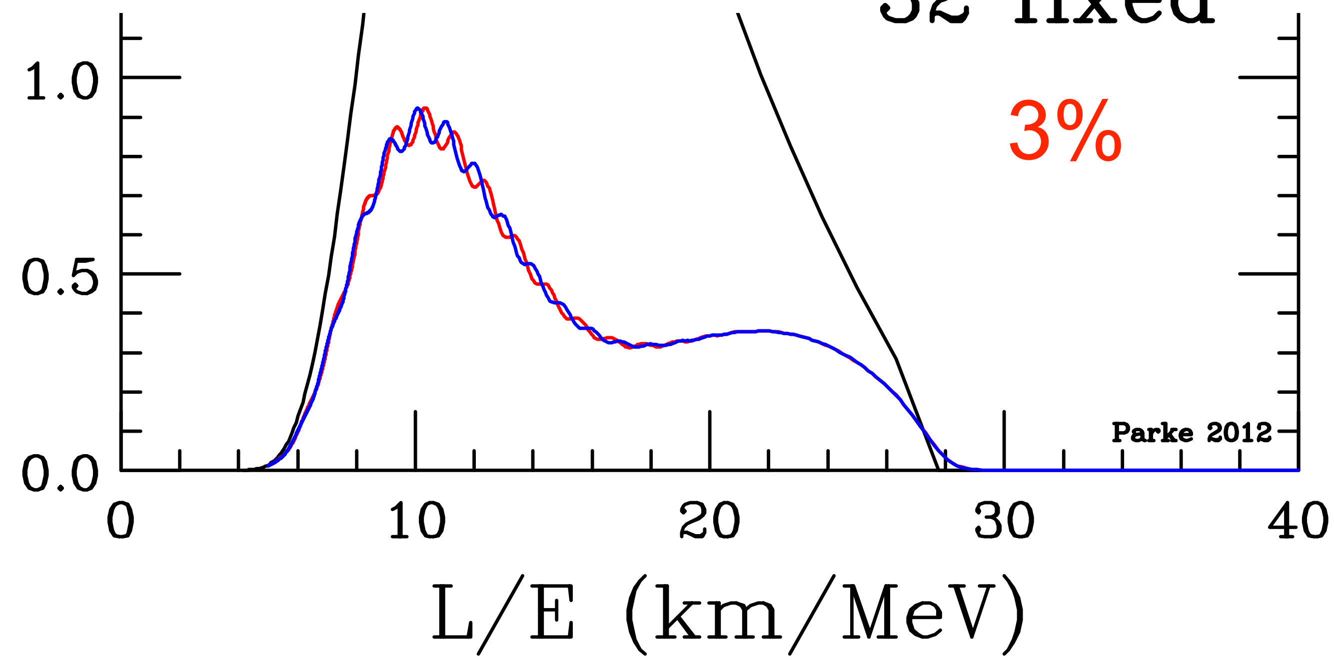
JUNO

perfect resolution, not $3\%/\sqrt{E/1\ \mathrm{MeV}}$



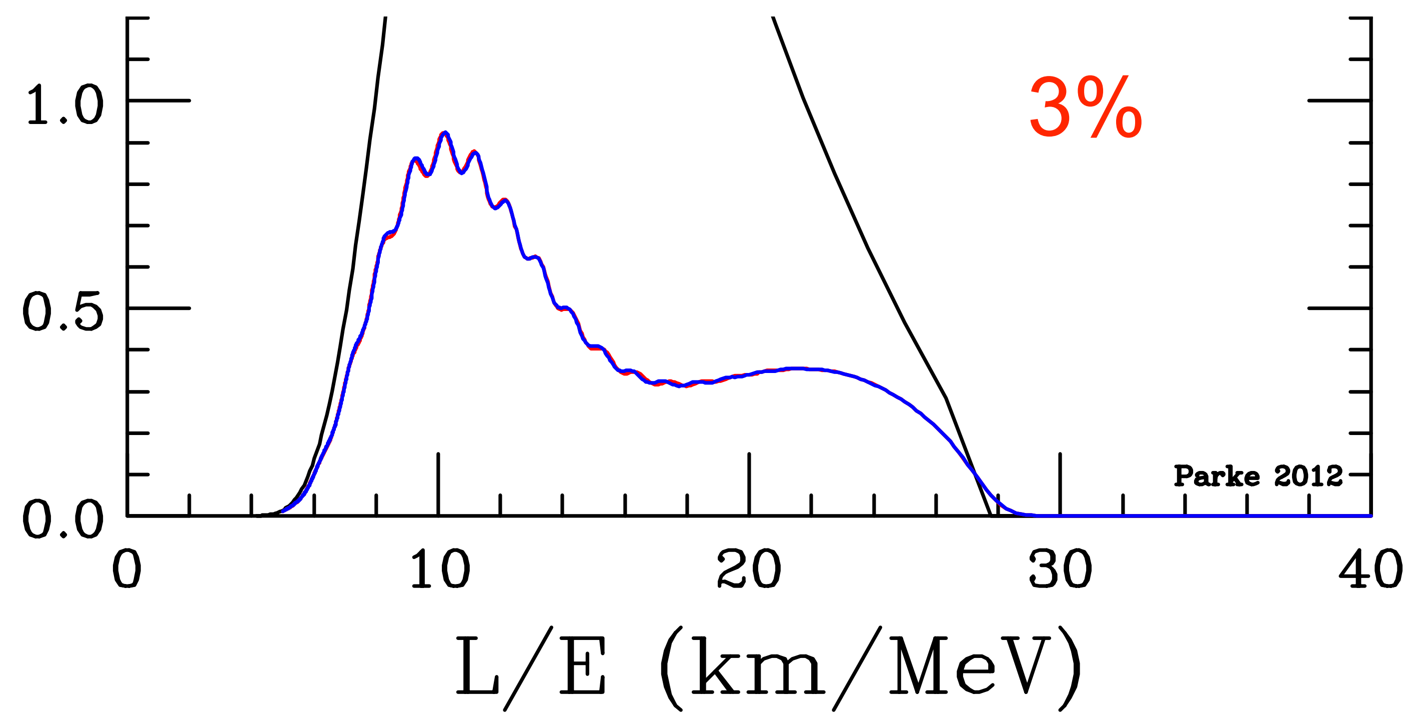
32 fixed

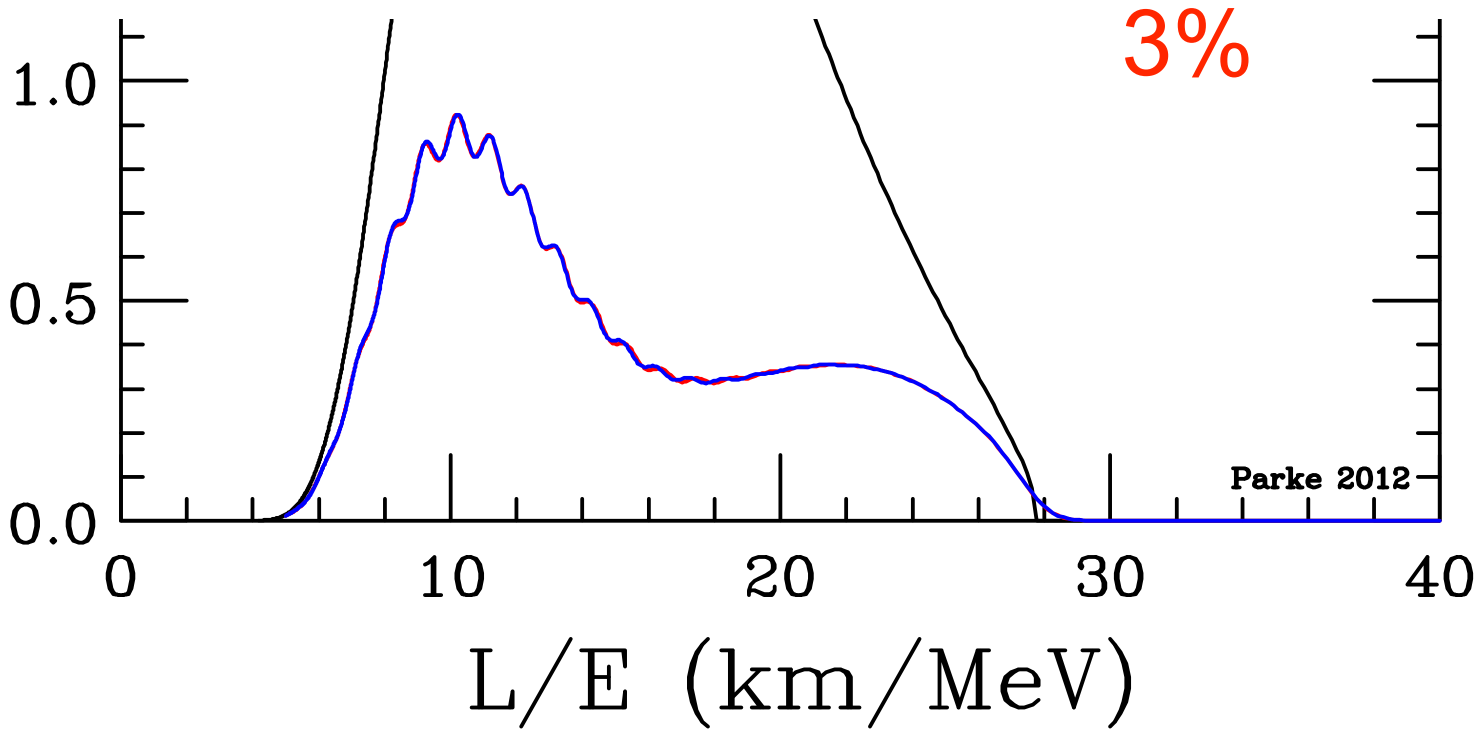
3%

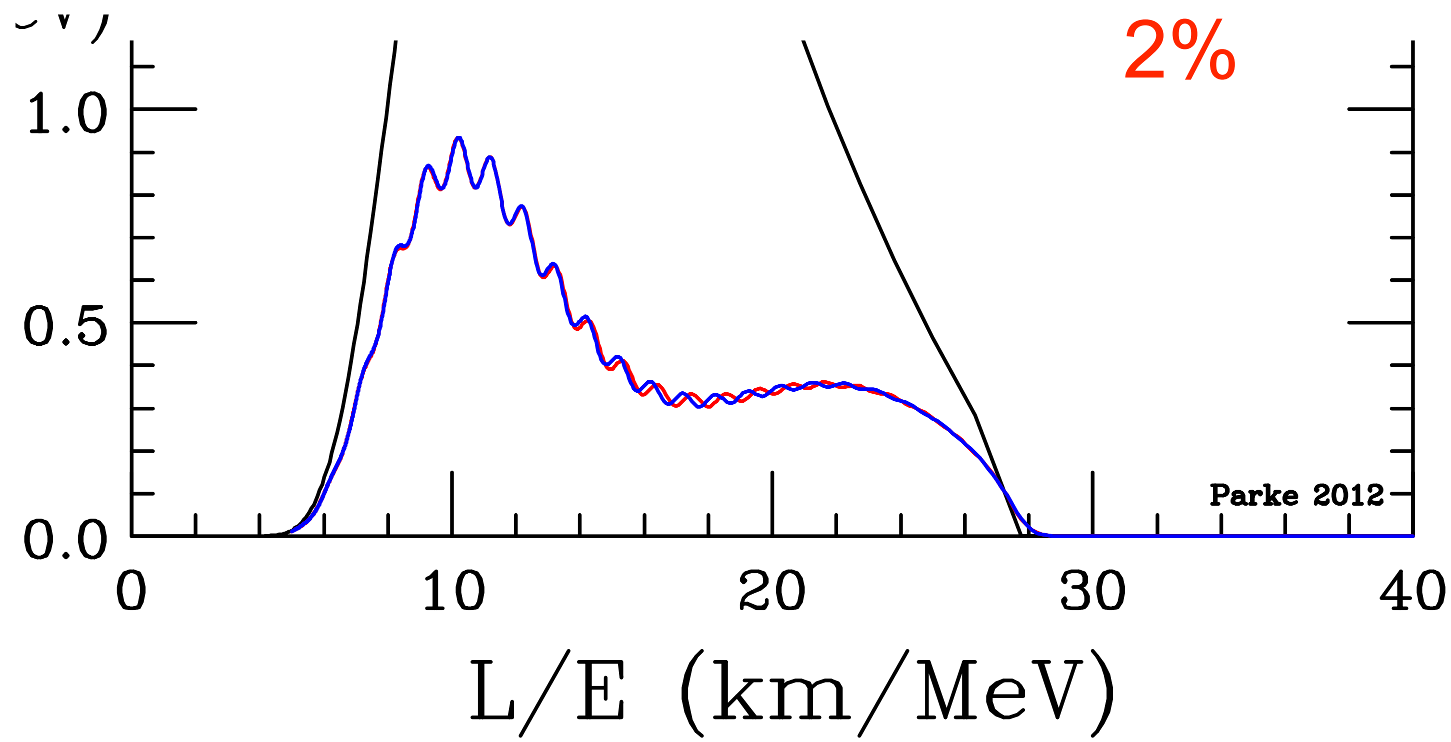


31 fixed

3%

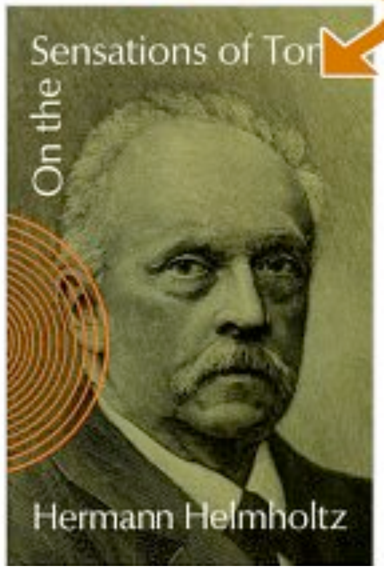



3%
1.0
0.5
0.0
0
10
20
30
40
Parke 2012
L/E (km/MeV)


2%
1.0
0.5
0.0
0
10
20
30
40
Parke 2012
L/E (km/MeV)

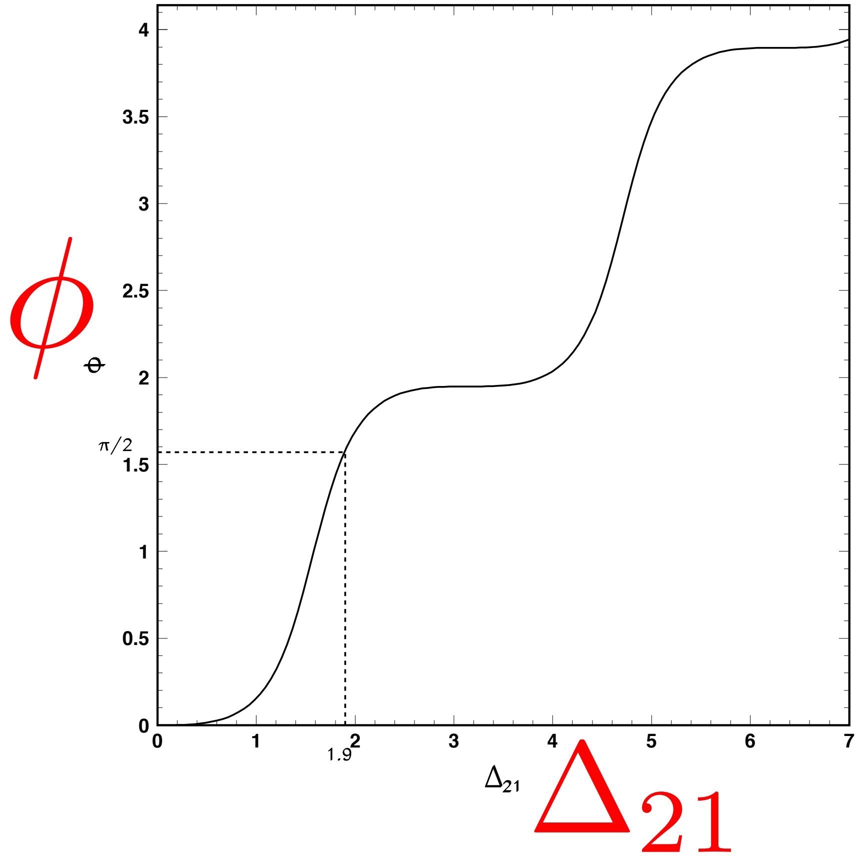
$$P_x(\bar\nu_e \to \bar\nu_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \frac{1}{2}\sin^2 2\theta_{13}\left(1 - \sqrt{1-\sin^2 2\theta_{12}\sin^2\Delta_{21}}\;\cos\Omega\right)$$

with $\Omega = (\Delta_{31}+\Delta_{32}) + \arctan(\cos 2\theta_{12}\tan\Delta_{21}).$



1875

$$\Omega = 2|\Delta_{ee}| \pm \phi$$



$\phi(\Delta_{21}\pm\pi) = \phi(\Delta_{21}) \pm 2\pi\sin^2\theta_{12},$

$$\Delta m^2_{ee} \equiv \frac{\partial\,\Omega}{\partial(L/2E)}\bigg|_{\frac{L}{E}\to 0} = \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

$$\phi = \{\arctan(\cos 2\theta_{12}\tan\Delta_{21}) - \Delta_{21}\cos 2\theta_{12}\}$$

NO phase advance

IO phase retardation

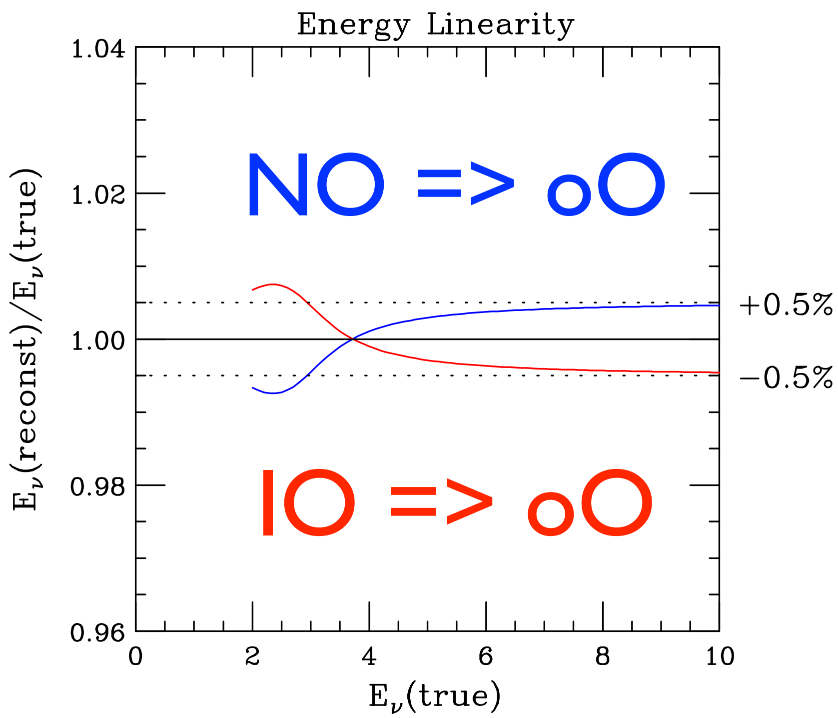
$$\Omega = (\Delta_{31} + \Delta_{32}) + \arctan\left(\cos 2\theta_{21} \tan \Delta_{21}\right) \quad \text{NPZ}$$

$$= 2\Delta_{ee} + \arctan\left(\cos 2\theta_{12} \tan \Delta_{21}\right) - \Delta_{21} \cos 2\theta_{12}$$

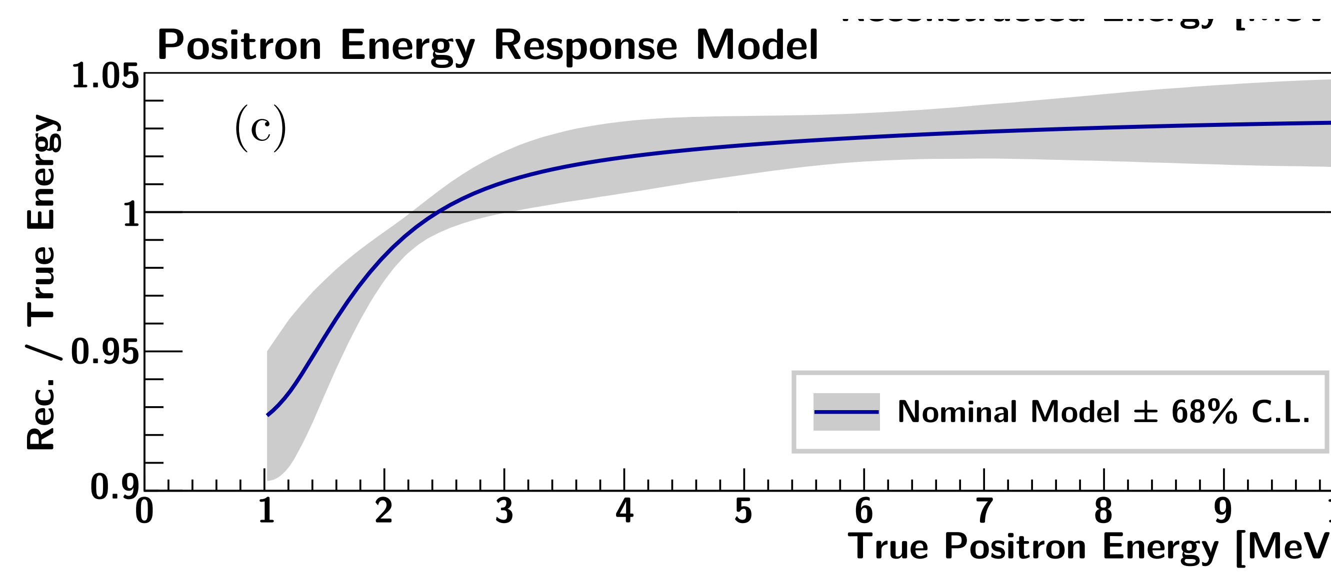
$$= 2\Delta_{32} + \arctan\left(\frac{\sin 2\Delta_{21}}{\cos 2\Delta_{21} + \tan^2 \theta_{12}}\right) \quad \text{DB}$$

$$= 2\Delta_{31} - \arctan\left(\frac{\sin 2\Delta_{21}}{\cos 2\Delta_{21} + \cot^2 \theta_{12}}\right)$$

Neutrino Energy Reconstruction



RENO

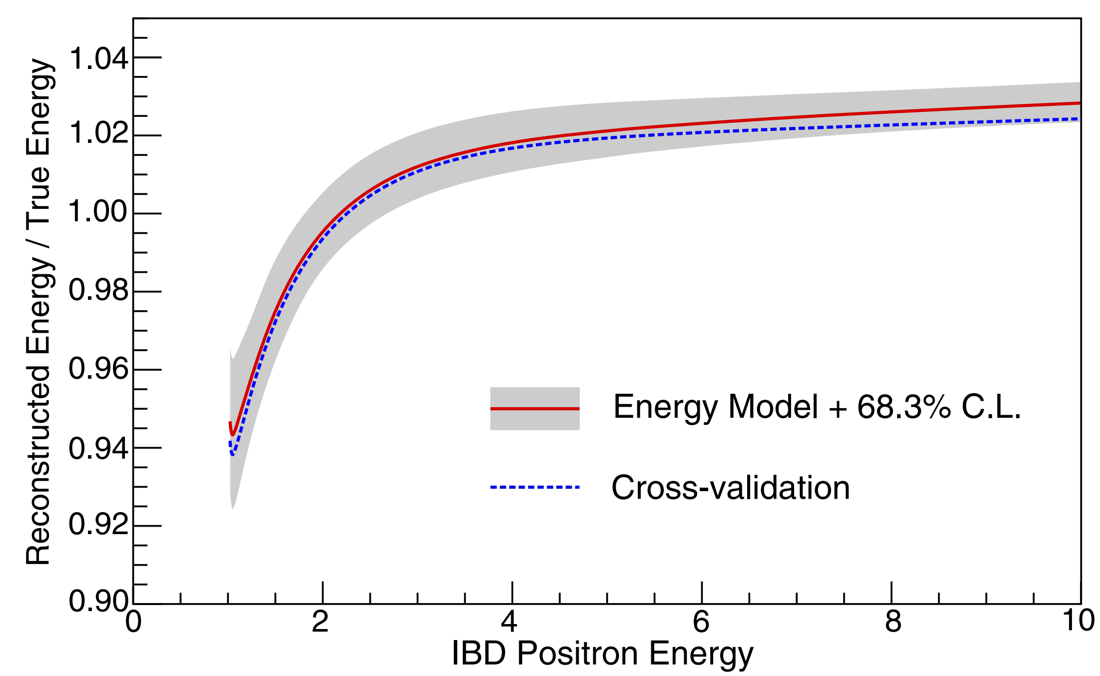


$$\Omega = 2|\Delta_{ee}| + \eta\,\phi$$

(NO, oO, IO) given by η=(1, 0, -1)

$$\delta\ (\Delta m^2_{ee}) \sim 0.5\%$$

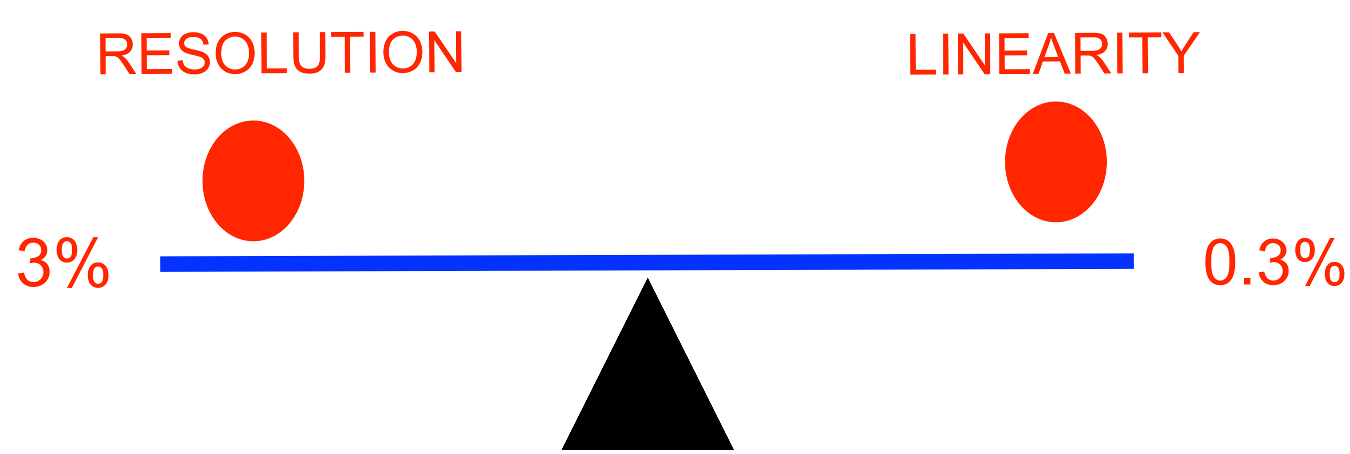
Daya Bay



Parke @ NOW 2008

- Energy Resolution to 3% or lower at 1 MeV
- Linearity to sub 1% precision for the reconstructed neutrino energy

	KamLAND	JUNO	RENO-50	
LS mass	~1 kt	20 kt	18 kt	20 x
Energy Resolution	6%/	~3%/	~3%/	
Light yield	250 p.e./MeV	1200 p.e./MeV	>1000 p.e./MeV	4 x
Linearity	1.9%	< 0.5%	< 0.5%	**> 4 x**



Matter Effects:

Neutrino Propagation in Matter:

$$i\frac{d}{dx}\nu \;=\; H\nu \qquad\qquad \boldsymbol{\nu} \equiv \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

$$H = \frac{1}{2E}\left\{ U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{bmatrix} U^\dagger + \begin{bmatrix} a(x) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \right\}$$

$$a \;=\; 2\sqrt{2}G_F N_e E \approx 1.52 \times 10^{-4} \left(\frac{Y_e \rho}{\mathrm{g.cm}^{-3}}\right)\left(\frac{E}{\mathrm{GeV}}\right)\mathrm{eV}^2.$$

if $\rho Y_e = 1.5$ g/cm^3 and $E = 10$ GeV then $a \approx \Delta m^2_{31}$

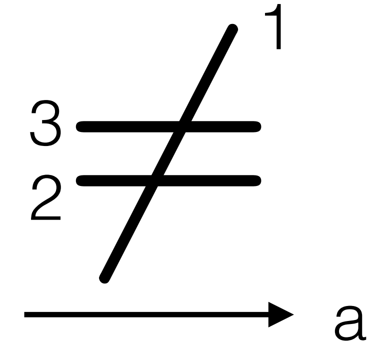
$E = 300\ MeV$ then $a \approx \Delta m^2_{21}$

Neutrino Evolution in Matter (conti):

$$U_{23}^\dagger(\theta_{23},\delta)\, H\, U_{23}(\theta_{23},\delta) = H_D + H_{OD}$$

D=diagonal OD= off-diagonal

$$(2E)\, H_D = \begin{bmatrix} a + s_{13}^2 \Delta m_{ee}^2 & & \\ & (c_{12}^2 - s_{12}^2)\Delta m_{21}^2 & \\ & & c_{13}^2 \Delta m_{ee}^2 \end{bmatrix}$$



$$\Delta m_{ee}^2 \equiv \cos^2\theta_{12}\Delta m_{31}^2 + \sin^2\theta_{12}\Delta m_{32}^2$$

!!! level crossing !!!

$$(2E)\, H_{OD}/\Delta m_{ee}^2 = s_{13}c_{13} \begin{bmatrix} & & 1 \\ & 0 & \\ 1 & & \end{bmatrix}$$

$$+\, c_{13}\; s_{12}c_{12} \left(\frac{\Delta m_{21}^2}{\Delta m_{ee}^2}\right) \begin{bmatrix} & 1 & \\ 1 & & 0 \\ & 0 & \end{bmatrix}$$

$$-\, s_{13}\; s_{12}c_{12} \left(\frac{\Delta m_{21}^2}{\Delta m_{ee}^2}\right) \begin{bmatrix} & 0 & \\ 0 & & 1 \\ & 1 & \end{bmatrix}$$

0.15

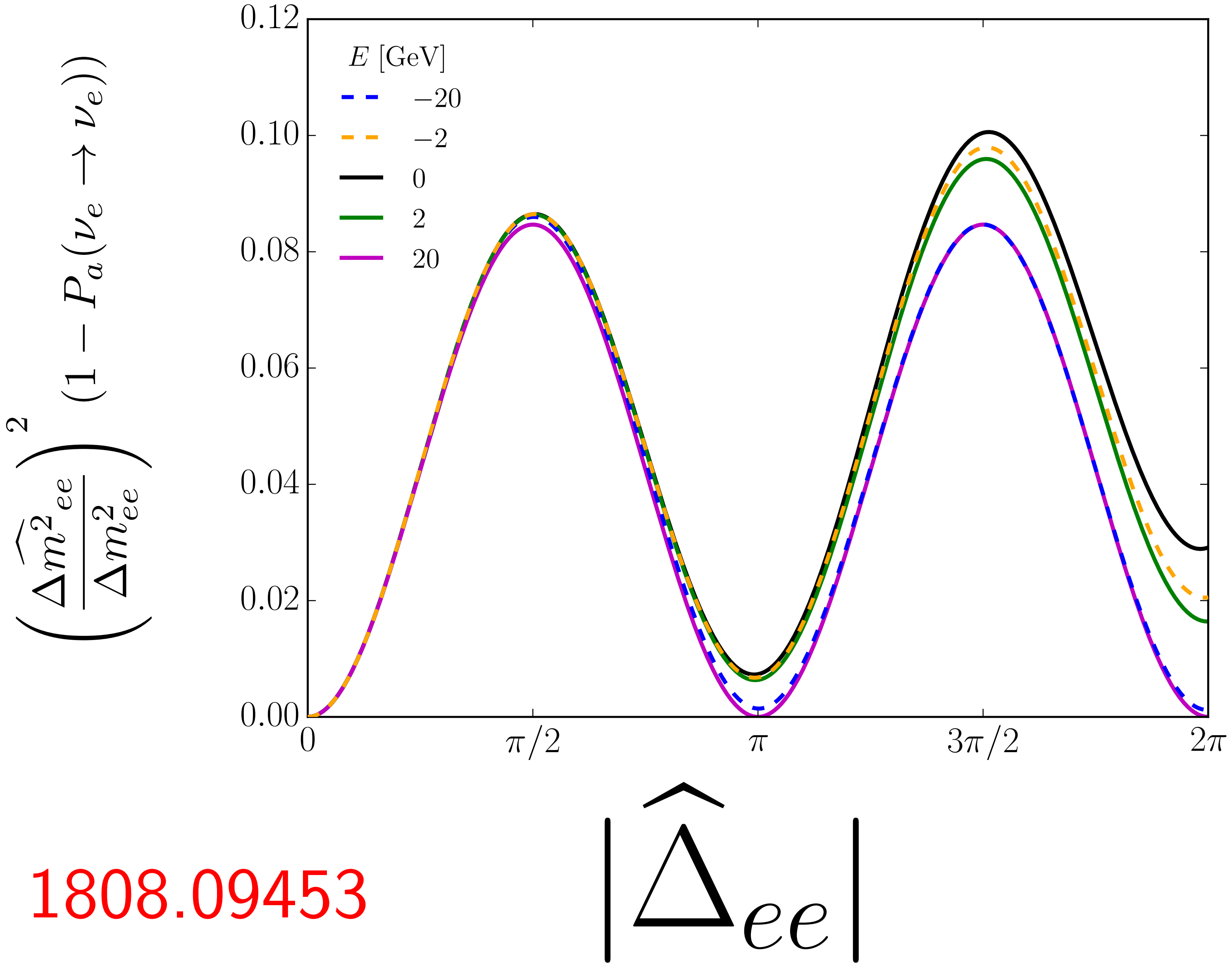
0.015

0.002

$\nu_e \to \nu_e$

$$P_a(\nu_e \to \nu_e) \approx 1 - \sin^2 2\theta_{13} \left(\frac{\Delta m^2_{ee}}{\Delta \widehat{m^2}_{ee}}\right)^2 \sin^2 \widehat{\Delta}_{ee}\,, \qquad \widehat{\Delta}_{ee} \equiv \Delta \widehat{m^2}_{ee} L/(4E)\,,$$

$$\Delta \widehat{m^2}_{ee} \approx \Delta m^2_{ee} \sqrt{(\cos 2\theta_{13} - a/\Delta m^2_{ee})^2 + \sin^2 2\theta_{13}}\,,$$



Denton, SP 1808.09453

In Matter:

$$\widehat{J} \approx \frac{J}{\mathcal{S}_{\odot}\,\mathcal{S}_{\rm atm}}\,,$$

two, two flavor resonance factors:

$$\mathcal{S}_{\odot} = \sqrt{(\cos 2\theta_{12} - c_{13}^2 a/\Delta m_{21}^2)^2 + \sin^2 2\theta_{12}}\,,$$

2 or 1 % effects !

$$\mathcal{S}_{\rm atm} = \sqrt{(\cos 2\theta_{13} - a/\Delta m_{ee}^2)^2 + \sin^2 2\theta_{13}}\,.$$

Denton & SP
1902.07185

fractional difference: $\sin^2\theta_{13}\left(\frac{\Delta m^2_{21}}{\Delta m^2_{ee}}\right)\cos 2\theta_{12} \sim 0.04\%$

Summary:

- Observation of Solar Neutrinos and Reactor Neutrinos have taught us a great deal the electron row of the PMNS matrix, about U_ei and Delta m^2 's.

- the concept of an effective Delta m^2, Delta m^2_ee, is useful for the shape analysis of reactor neutrinos.

$$\Delta m^2_{ee} \text{ is } \nu_e \text{ average of } \Delta m^2_{31} \text{ and } \Delta m^2_{32}$$

- Short baseline reactor experiments can constrain (maybe measure) Delta m^2_21 at twice the KamLAND value.

- the generalization of Delta m^2_ee into matter, is useful for understanding neutrino oscillations in matter for DUNE and T2HK(K)

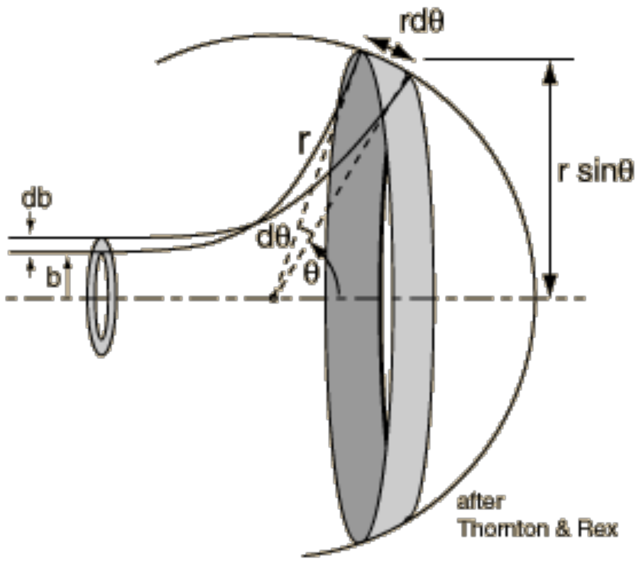
$$\boldsymbol{\Delta m^2_{ee}\sqrt{(\cos 2\theta_{13} - a/\Delta m^2_{ee})^2 + \sin^2 2\theta_{13}}}$$

Ernest Rutherford, master of simplicity

By Ashutosh Jogalekar | August 30, 2013 | 6

Ernest Rutherford, emperor of the atomic domain (Image: Wikipedia Commons)

"theorists play games with their symbols while we discover truths about the universe". And yet

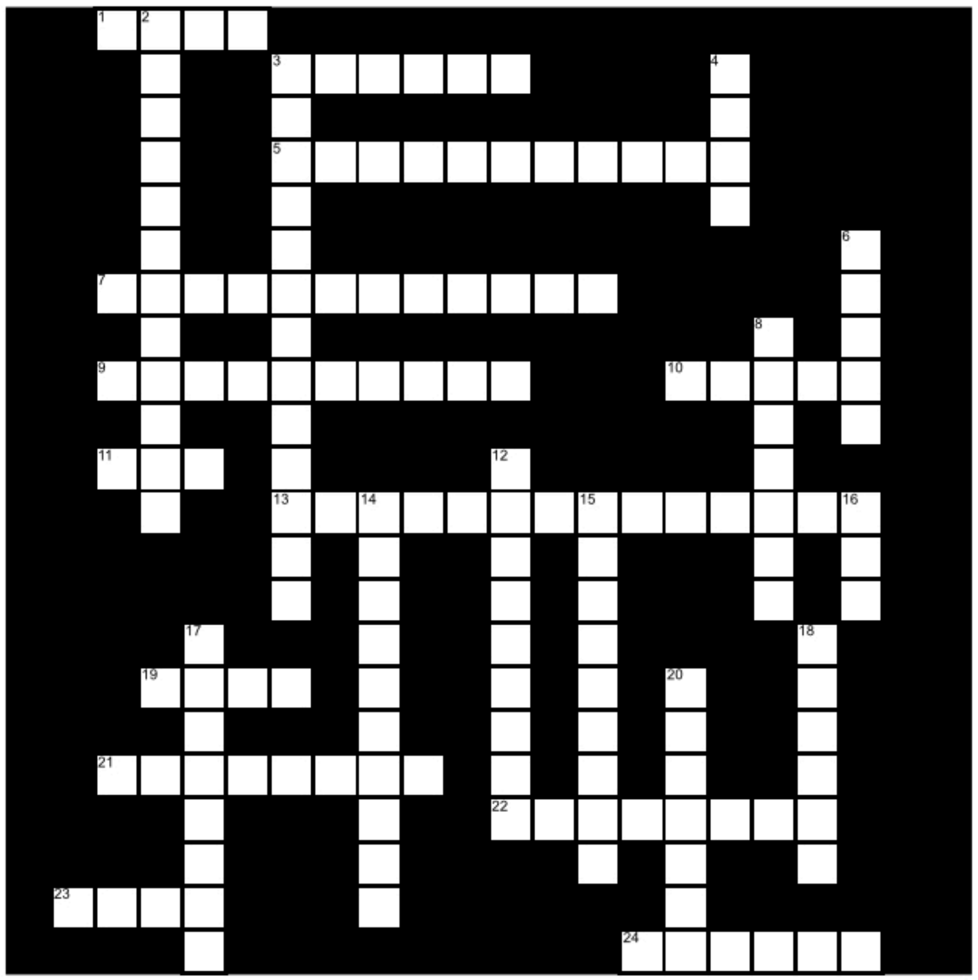


$$\sigma = \pi Z^2 \left(\frac{ke^2}{KE}\right)^2 \left(\frac{1+\cos\theta}{1-\cos\theta}\right)$$

he had an eye for theoretical talent that allowed him to nurture Niels Bohr, as dyed-in-the-wool a theoretician and philosopher as you could find.

Neutrino Crossword

Neutrino Puzzle



Across

1 When Potassium 40 decays does it emit neutrinos or antineutrinos ?

3 In 1966 a popular book on neutrinos was written by

5 How many neutrinos, in log base 10, does the Sun emit per second ?

7 What important effect did Wolfenstein discover in 1978 ?

9 What percentage of the energy from a Supernova is released in neutrinos ?

10 Neutrinos from Decay of this element have been observed

11 Solar Neutrino Unit

13 Why are neutrino nucleon cross sections so challenging to calculate ?

19 Neutrino Propagation states

21 What distinguishes a neutrino from and antineutrino ?

22 Little neutral one

23 What happens to oscillation length if Planck's constant goes to zero ?

24 If neutrinos are Majorana which number symmetry is violated ?

Down

2 Quantum mechanical interference of the mass eigenstate leads to ...

3 What do reactors emit ?

4 Why Pauli did not go to the scientific meeting where his invention of the neutrino was announced ?

6 When crossing a high energy neutrino beam is it better to cross in front or behind a concrete wall ?

8 Powers Nuclear Reactors

12 Who gave the SuperK atmospheric neutrino talk at Neutrino 1998

14 Why is |U_e1|^2 larger than |U_e2|^2 or |U_e3|^2 ?

15 The Argon in earth's atmosphere comes from decay of which element ?

16 Which experiment "nailed" the solar neutrino anomaly ?

17 The invariant that controls the size of CP violation was invented/discovered by this woman physicist

18 Neutrino Interaction States

20 Zombie neutrinos

npc.fnal.gov/question/

Neutrino Question • Neutrino Physics Center

Fermilab

Neutrino Question:

You receive an email from a high school student taking Advanced Placement Physics, asking:

"Why are you studying Neutrinos?"

Trevor Nichols

The purest answer to why we study neutrinos is simply that we are curious. Neutrinos are the most abundant of the fundamental particles, yet we know the least about them. Beyond simple curiosity, neutrinos are useful, not so much for what they can do themselves, but for what they can tell us about other things.

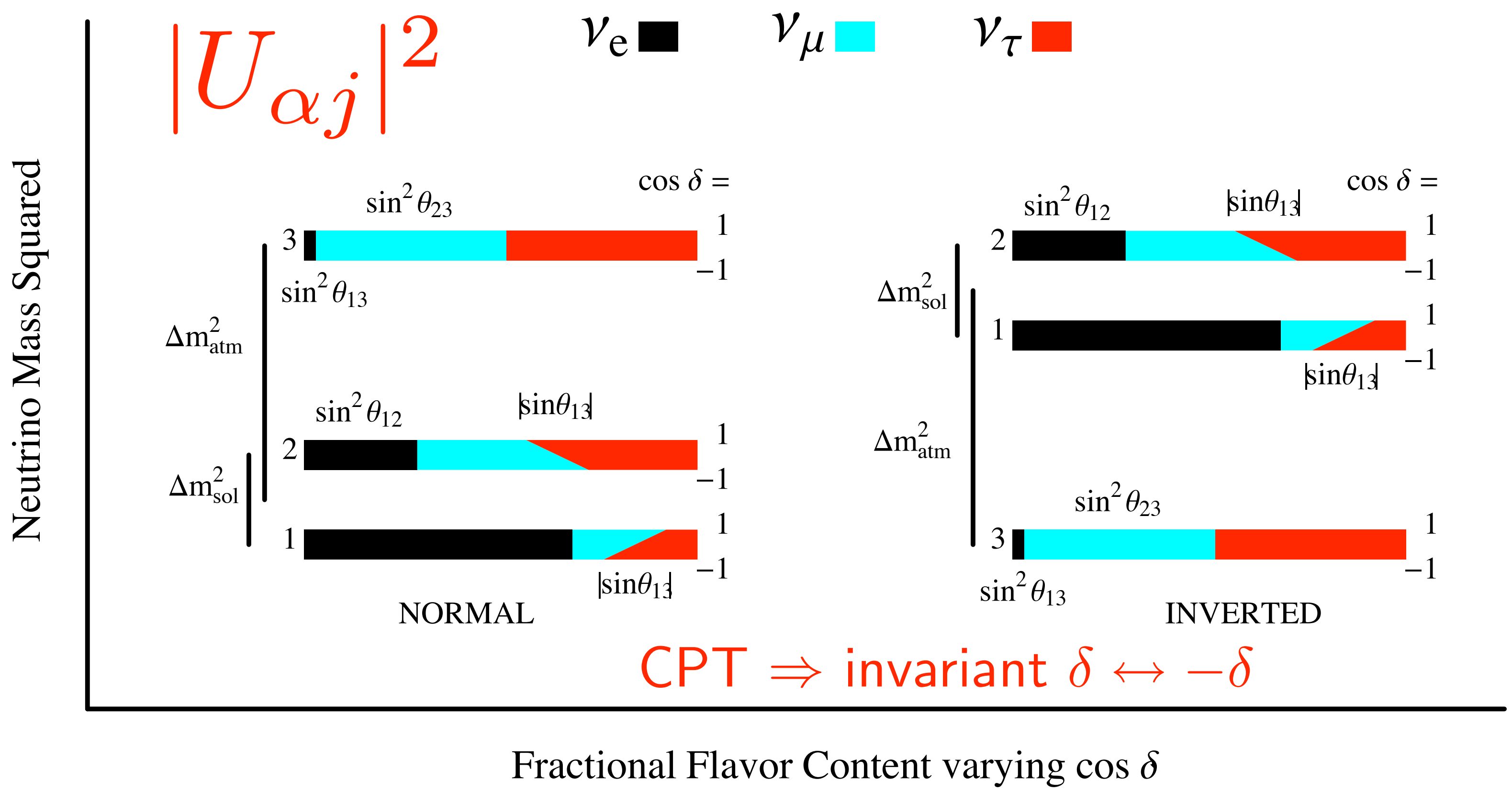
Neutrinos provide a new lens through which to view the universe. Black holes are not detectable using visible light. They do not emit any. Yet, when we look at the universe using X-rays, we can now see swirling accretion discs, indicating the presence of black holes. Similarly, neutrinos provide visibility to that which we previously could not see.

Neutrinos are created in nuclear reactions, which are abundant in the cores of stars. Unlike photons, neutrinos can escape a star (or any other object) unaltered by the material they must pass through to escape. Upon detection, neutrinos reveal information about the originating reaction.

extras

Summary:

- Labeling massive neutrinos: $|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$



$$\sin^2\theta_{12} \sim \frac{1}{3}$$

$$\sin^2\theta_{23} \sim \frac{1}{2}$$

$$\sin^2\theta_{13} \sim 0.02$$

$$0 \le \delta < 2\pi$$

$$|\Delta m^2_{21}| = |m^2_2 - m^2_1| = 7.5 \times 10^{-5}\ \mathrm{eV}^2 \qquad L/E = 15\ \mathrm{km/MeV} = 15{,}000\ \mathrm{km/GeV}$$

$$|\Delta m^2_{31}| = |m^2_3 - m^2_1| = 2.5 \times 10^{-3}\ \mathrm{eV}^2 \qquad L/E = 0.5\ \mathrm{km/MeV} = 500\ \mathrm{km/GeV}$$

How Does Daya Bay Define Δm^2_{EE} ?

arXiv:1310.6732

ν_j and ν_i. Since $\Delta m^2_{21} \ll |\Delta m^2_{31}| \approx |\Delta m^2_{32}|$ [1], the short-distance ($\sim$km) reactor $\overline{\nu}_e$ oscillation is due primarily to the Δ_{3i} terms and naturally leads to the definition of the effective mass-squared difference $\sin^2\Delta_{ee} \equiv \cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}$ [11].

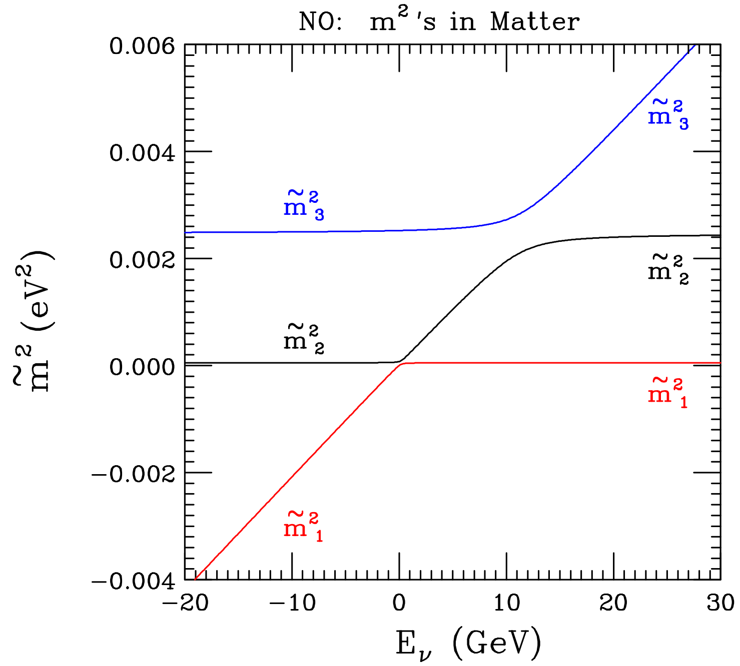
1505.03456v1

[8] $\sin^2\Delta_{ee} \equiv \cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}$, where $\Delta_{ji} \equiv 1.267\Delta m^2_{ji}(\mathrm{eV}^2)[L(\mathrm{m})/E(\mathrm{MeV})]$, and Δm^2_{ji} is the difference between the mass-squares of the mass eigenstates ν_j and ν_i.

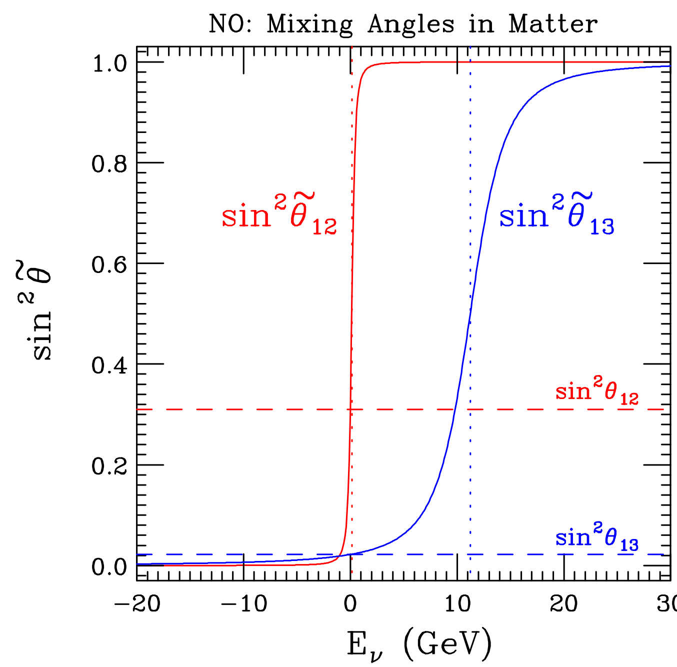
Mixings and Masses in Matter:

0th Order:

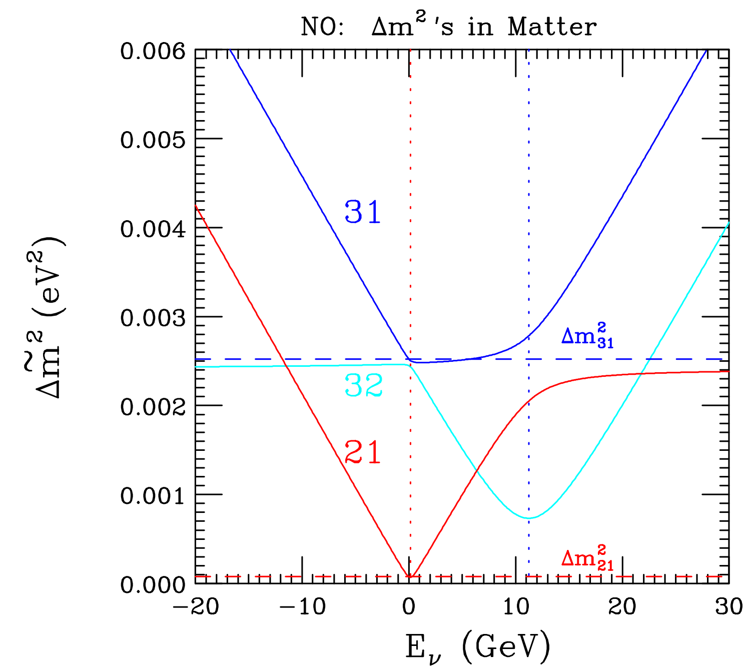
θ_{23}, δ unchanged



NO:
for IO figures see 1604.08167



$$\widetilde{\theta}_{13}, \widetilde{\theta}_{12}$$



$$\Delta \widetilde{m^2}_{31}, \Delta \widetilde{m^2}_{21}$$

After 2 rotations:

$\tilde{s}_{12} \equiv \sin\tilde{\theta}_{12}$, etc

$$(2E)\, H_{OD}/\Delta m^2_{ee} \quad = \quad \sin(\tilde{\theta}_{13}-\theta_{13})\; s_{12}c_{12} \left(\frac{\Delta m^2_{21}}{\Delta m^2_{ee}}\right) \begin{bmatrix} & & -\tilde{s}_{12} \\ & & \tilde{c}_{12} \\ -\tilde{s}_{12} & \tilde{c}_{12} & \end{bmatrix}$$

$$\sin(\tilde{\theta}_{13}-\theta_{13}) \approx s_{13}c_{13}\left(\frac{a}{\Delta m^2_{ee}}\right)$$

4×10^{-4}

for $E = 2$ GeV and $\rho = 3$ g.cm^{-3}

zero in vacuum